Development of a Composite Wheel Rim for an FSAE Car

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The ratio between a vehicle's sprung and unsprung mass significantly affects the control characteristics and handling of the vehicle. The lighter the unsprung mass, the faster the response time will be, allowing a more consistent vertical load through the tyres and consequently a more consistent level of friction between the car and the road. This allows for better acceleration, braking and cornering performance for the vehicle, as well as increased driver confidence, providing an advantage on the race track. This thesis will investigate the reduction of unsprung mass through the development of a composite wheel rim designed to mate with a machined aluminium centre. This thesis will include an analysis of currently used rims by the UNSW@ADFA FSAE team, the design of a composite rim and the manufacturing processes that should be used to produce a composite rim.

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Nomenclature

CAD = Computer Aided Design
Cf = Coefficient of friction
CFRP = Carbon Fibre Reinforced Plastic
COTS = Commercial Off the Shelf
ECU = Engine Control Unit
FEA = Finite Element Analysis
FRP = Fibre Reinforced Plastic
FSAE = Formula Society of Automotive Engineers
GFRP = Glass Fibre Reinforced Plastic
GPa = Gigapascals
k_1 =Spring constant of the tyre
k_2 = Wheel rate (equivalent spring constant)
m_1 = Unsprung mass
m_2 = Sprung mass
MOTS = Modified Off The Self
NDI = Non Destructive Inspection
PPE = Personal Protective Equipment
Prepreg = Pre-impregnated fabric
UTS = Ultimate Tensile Strength
ω_0 = Undamped natural frequency
x_1 = Unsprung mass position
$\ddot{x}_1$ = Unsprung mass acceleration
x_2 = Sprung mass position
$\ddot{x}_2$ = Sprung mass acceleration

I. Introduction

The Academy Racing 2009 car was a conceptual re-design of all cars previously designed by the team. The earlier four cars focused on integrating as much technology into the cars as possible, creating a car that whilst performing competitively on paper and in simulation software ultimately resulted in an under tested car that was not able to fully realise the designed potential. The 2009 model focused on building a simple, reliable, lightweight car that allowed for more testing time and further development in conjunction with the drivers. Preliminary actions in this area have seen a reduction of wheel sizes from 13 to 10 inches, the removal of unnecessary systems, that while representing advanced technology slow the production of the car and reduce testing time, and extensive finite element analysis (FEA) of all components being designed for the vehicle. The team's 2012 car is planned to have significant changes with the selection of a smaller lighter engine and the development of an aluminium monocoque chassis further decreasing the vehicle weight. The majority of this planned weight reduction is on the sprung mass, the mass of the vehicle not including the suspension system of the car. Additionally the vehicles suspension takes the form of a beam axle which reduces the production time of the system at the cost of a weight increase for the components. This decreases the ratio between sprung and unsprung mass, and thus increases the response time of the suspension system (Inaman, 2001). While this reduces the vehicles roadholding characteristics the overall reduction in mass allows for greater acceleration and performance.

This thesis strives to develop a composite wheel rim to use with a lightweight aluminium centre to reduce the unsprung mass of the vehicle and as such decrease the suspension response time for greater control. This will work toward bringing the sprung to unsprung mass ratio closer to the original, and subsequently allow for further reduction of the unsprung mass. The wheel and tyre assembly contribute a significant portion of the vehicles rotational inertia as the radius of gyration is much larger than that of the brake discs, hubs and drive train components. Reducing the vehicles rotational inertia will improve the transient response time in both braking an acceleration.

II. Aim

The aim of this thesis is to produce a composite wheel rim that is lighter, stiffer and more dimensionally accurate then the currently used aluminium wheels. This can be broken down into four sub aims:

1. Develop wheel load cases to correctly determine the forces that will be imparted on the wheel by the tyre,
2. Ascertain stiffness of current wheels for developed load cases,
3. Design and manufacture composite wheels to exceed the specifications of the current rims,
4. Manufacture sample rims to ensure validity of the concept and prove the layup design.

III. Thesis Scope

This project will contribute to a variety of projects intended to decrease the weight and increase the performance of the UNSW@ADFA FSAE car. The wheel rim will be designed in conjunction with new uprights with integrated brake callipers. The combined decrease in weight will allow improved vehicular acceleration capability thereby reducing lap times and improving handling, creating a more drivable car.
To achieve this the project is broken down into three phases. The phases are as follows: (1) Investigation of current rims to ascertain their current structural properties; (2) Design an initial rim that will meet the performance requirements of the original aluminium rim; (3) Manufacturing of the moulds and composite rim samples.

A. Phase One

This phase will include the measuring of wheel loads and translating them into the wheel load cases using the ACME Racing design load cases document. The current rim deflection will be measured through static loading that is representative of in service loads. These deflections will be used as a bench mark that the composite rims have to achieve when loaded in the same manner.

B. Phase Two

The rim is to be designed to meet the minimum stiffness and strength requirements using the known critical rim dimensions and properties. The materials will then be altered to observe the effect on stiffness, cost and weight on the rim to provide the best compromise between the three.

C. Phase Three

This phase consists the design and development of moulds from which the final part is to be made and the subsequent manufacture of the prototype composite rim. This manufacturing phase will require liaison with the school workshop and also the composites lab to use each departments facilities and manufacturing knowledge.

IV. Vehicle dynamics

In order for a car to remain controllable the tyre must be in constant contact with the ground and a considerable amount of (normal) force must be maintained (Milliken & Milliken, 1995). To do this the cars suspension system must be able to follow the road and all its imperfections. The suspension response time can be characterised by its natural frequency (Staniforth, 2006). A simple model of the suspension system assumes the sprung mass to be fixed, the tyre rigid and the unsprung mass to oscillate freely ignoring damping (Milliken & Milliken, 1995). This system is characterised by the equation:

$$\omega_0 = \sqrt{\frac{m_1}{k_2}}$$

Where $\omega_0$is the undamped natural frequency, k_2 the wheel rate (spring constant taking into account any motion ratios) and $m_1$the mass of the unsprung components .From this equation it can be derived that a decrease in the unsprung mass will increase the natural frequency and allow the suspension to respond faster. While the same results can be achieved by increasing the spring stiffness this also decreases the suspension travel and means that the suspension relies on an increasingly smooth track. As such the ideal unsprung weight is zero, so the suspension can be relatively softly sprung and the wheel can follow all undulations in the road without losing contact. Using a 2 degree of freedom system taking tyre vertical stiffness in to account the equations of motion become (Inaman, 2001):

$$m_1\ddot{x_1} = -k_1x_1 + k_2(x_2 - x_1)$$

$$m_2\ddot{x}_2 = -k_2(x_2 - x_1)$$

Where $\ddot{x_1}$ and $\ddot{x}_2$ are the accelerations of the unsprung and sprung mass respectively m_2 and $m_1$are the masses, k_1 and k_2 are the spring rate of the tyre and the wheel rate respectively and x_1 and x_2 are the positions of the suspension and the chassis respectively. Rearranging this equation to view one acceleration predominantly as a function of the other and the masses gives:

$$\ddot{x}_1 = -\frac{x_1 k_1}{m_1} - \frac{m_2 \ddot{x}_2}{m_1}$$
$$\ddot{x}_2 = -\frac{x_1 k_1}{m_2} - \frac{m_1 \ddot{x}_1}{m_2}$$

Decreasing m_1 will increase $\ddot{x}_1$ which will allow the suspension to keep in constant contact with the road. An increase in m_2 will lower $\ddot{x}_2$ keeping the chassis position relatively constant. It is shown then that as $\frac{m_2}{m_1}$ tends towards ∞ the response of the suspension is increased and the displacement of the chassis is decreased, providing a more comfortable ride for the driver while improving the handling.
To improve the ratio of masses it is possible to use a ballast to increase the sprung mass, however applying newtons second law of motion to this situation states that this will reduce the acceleration of the car and in a racing situation increase the cars lap times. This leaves the most desirable solution to the problem to reduce the unsprung mass of the vehicle.

V. Current Products

There are a limited number of composite wheel products on the market for road cars, race cars and motorbikes in varying sizes. However due to the emerging nature of this technology manufacturers are not willing to provide information on their construction techniques. Further to this, the costs for purchasing wheels of this nature are very high, with a pair of motorcycle wheels costing close to $4500 (Harwood Performance Source, 2010).
Due to the high costs of current products and the limited information provided by manufacturers, the design of a composite wheel rim has to be conducted from grassroots. The bespoke nature of the suspension concept used on the current Academy Racing car requires a 'deep dished' wheel with a high offset to attain a low scrub radius.

VI. Composite Materials Literature Review

A. Material selection

Composite materials are light weight with high specific stiffness and strength compared to traditional isotropic materials such as metals (Strong, 2008). They are comprised of two or more materials working together, where each material retains its own identity and contributes its own structural properties to create a synergistic material with better structural properties then is constituents (Dorworth, Gardiner, & Mellema, 2009). Common examples of composites are wood, concrete and Glass Fibre Reinforced Plastic (GFRP) which can be found in all manner of common items from buildings to sporting equipment (Mallick, 2008). The stiffness of a composite material principally occurs along the fibre axis, with the material being quite flexible in the case of off axis loading. As such orientating the fibres to meet the specific requirements of the load paths allows a product to be manufactured that is both light weight and very stiff. The use of a FRP in designing a wheel will allow the final product to be tailored to meet the specific operational loads to which it will be subjected. Thus creating a stronger, stiffer and lighter final part. In FRP the two constituents are known as the fibre and matrix to make up the composite laminate. The fibre properties dominate the tensile strength and the tensile modulus of the material, while the matrix dominated structural properties include compression interlaminar shear and ultimate service temperature (Dorworth, Gardiner, & Mellema, 2009). As such the selection of both fibre and matrix need to be considered as part of the initial phase of the design to ensure that the appropriate constituents are chosen for the application.

B. Fibre selection

Due to cost and availability three fibres have been considered for use in the manufacture of the wheels, these fibre families are glass, carbon and aramid fibres. Qualitatively, all three families have high ultimate tensile strength (UTS) (above 3GPa per fibre) however all

	Density (kg/m^3)	Tensile Strength (GPa)	Tensile Modulus (GPa)	Specific Strength	Specific Modulus
PAN-SM Carbon	1800	4.1	231	0.002278	0.128333
PAN-IM Carbon	1800	5.1	295	0.002833	0.163889
PAN-HM Carbon	1900	4.8	395	0.002526	0.207895
S-2 Glass	2480	4.5	89.5	0.001815	0.036089
Kevlar 29	1440	3.6	82.7	0.0025	0.057431
Kevlar 49	2490	3.6	130.3	0.001446	0.052329

Table 1. A Comparison of various types of fibres depicting their specific properties. (Dorworth, Gardiner, & Mellema, 2009)

have greatly varying tensile modulus from as low as 11GPa for some glass to in excess of 400 GPa for carbon. The increase in modulus is offset by the decrease in ductility and as such the reduced resistance to shock loading and the increased tendency to fracture as a result. The carbon family has the highest specific modulus, and the intermediate and high modulus fibres having the highest specific strength (Table 1). Considering the specific strength and modulus as the primary design factor carbon is the fibre family that has been chosen to use in the design of the composite wheel. Carbon also exhibits far less fatigue than a metal would and therefore does not have the fatigue life implications (Barbero, Introduction to Composite Materials Design, 2011). Handling of dry carbon fabric poses little hazards to the human body, however post cure operations create hazards such as sanding, grinding and milling as these processes create small particles that can cause irritation to the lungs. Depending on the size of these particles they can become permanently lodged in the lining of the lung and diminish the function of the organ. As such, the appropriate PPE is required when working with composite materials (McBeath, 2000).

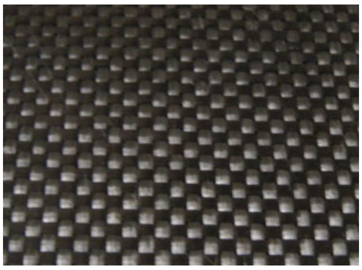

Figure 1. Plain weave carbon fiber. *Image courtesy of compositeenvisions.com*

C. Fabric Selection

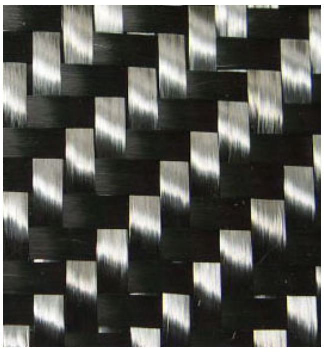

Figure 2. 2x2 Twill weave carbon fibre. *Image courtesy of modbargians.com*

Fibres can be biased to provide strength in the required directions. Therefore, selection of the particular weave of fabric to be used is important to the final products properties. To weave a fabric there are two fibre orientations used, these orientation names are warp and fill. Warp fibres are continuous fibres running along the length of the fabric roll, fill fibres are perpendicular running across the roll. Important considerations in fabric selection are the fabric's drapability, the ease at which a fabric will conform to a surface without wrinkling (Barbero, Introduction to Composite Materials Design, 2011), and the comparative strength of the fabric along the principle axes, the specific fabric orientation is defined by the intended use of the fabric.

Plain weave is the most common fabric used in composite layup as there is no warp or fill dominant face to consider during manufacturing, meaning that it has the same properties in one direction as well as in the perpendicular direction which can be used to easily create and orthotropic part. Plain weave fabrics have a comparatively low strength due to the constant crimps of the weave and their relatively low ply count. They are difficult to form over complex curves as the fibres will lock when the fabric is sheared (Dorworth, Gardiner, & Mellema, 2009).

Figure 3. Unidirectional stitched carbon fibre. *Image courtsey of made-in-china.com*

Twill fabric is when one fill yarn is fed over two and then under two warp yarns, appearing to create a constant diagonal of fill yarns and warp yarns alternately. This is a common type of weave and has an improved drapability over a complex curve when compared to a plain weave as the fibres have more freedom of movement. It still exhibits the same properties in two perpendicular directions (Strong, 2008).

Unidirectional stitched fabrics consist of numerous tow's stitched together so the fabric is almost 100% biased in one direction with excellent strength as there is no crimping of the main fabric. This fabric is useful if there exists one particular direction that requires a significantly higher strength than any other direction, for example the external faces of a beam in a three point bending test which are loaded almost entirely in tension and compression along the beams axis (Hilado, 1974).

Tape is a narrow fabric that can be woven, braided or stitched and is usually used to wind onto a mandrel mould for making axis symmetric components.

D. Matrix selection

The use of epoxy as a matrix has been chosen for this project. It is easy to work with, reasonably inexpensive and is the most common form of carbon reinforced pre-impregnated fabric (prepreg) (Rosato, 1997), making it easier to obtain than some of the other resins available. Furthermore epoxy resin systems emit limited quantities of styrene's compared to other resins and as such is less of a risk to the health of the manufacturer and other people working in the area (Huntsman, 2004). Epoxy resins can have an operational service temperature of up to 180 degrees C. They have high physical and adhesion properties and as they are the main resin used in the composite industry, make their acquisition for a low cost project more realistic than a rarer material. In its cured form, epoxy is considered to be a relatively safe material; it is not known to cause any allergic reactions. It is not carcinogenic and even in its dust form it is officially considered to be little more than a nuisance. However prior to mixing the two parts of the epoxy are moderately toxic and can be corrosive. The two components have low vapour pressures so there is little risk to the user unless the chemicals are directly spilt onto them (Dorworth, Gardiner, & Mellema, 2009).

	Strength Primary	Strength Secondary	Drapability
Plain	Moderate	Moderate	Poor
Twill	Moderate	Moderate	Moderate
Unidirectional	Excellent	Poor	Excellent

Table 2. Comparative properties of fabric weave. *Table 2 shows that twill fabric is moderate as an all purpose fabric, but unidirectional fabric offers excellent strength in specific directions allowing areas to be tailored for a specific load.* (Dorworth, Gardiner, & Mellema, 2009)

E. Core Materials

The use of a light weight core material can reduce the weight of a product by providing an increase in the height of the cross section of the layup. This increases the moment of area of the product and consequently increases the stiffness and reduces the stress. When the core is lighter than the material it replaces, it decreases the weight of the component and increases the specific stiffness and specific strength of the composite particularly in bending (Dorworth, Gardiner, & Mellema, 2009). When a core is used it is referred to as a sandwich panel construction. Cores can be made of any light weight material that will bond to a composite skin. A core can be a material as simple as balsa wood or as complex as X-COR® a carbon fibre reinforced foam developed for use in aircraft manufacture. Common cores also include paper, Kevlar® and aluminium honeycomb panels.

F. Bi-Metallic Corrosion

When carbon and metals, particularly aluminium come into contact they creates a galvanic cell that causes corrosion (Mallick, 2008). This corrosion takes time to occur and its prevention needs to be seriously considered in the design and manufacture with respect to the anticipated service life and environmental conditions of the design of a carryover item such as a carbon fibre wheel rim.

VII. Integration With Existing Components

As this project is to integrate with already designed components, the spatial allowances need to be considered in the design process, the primary structures of concern are the wheel centres and the tyre beads, however the space envelope assigned to the uprights, steering arms and beam trailing arms all need to be considered. All of these components were designed using the current wheel internal profile, this profile will define the maximum limits of the composite rim to avoid contact at all of the designed positions of the wheel.

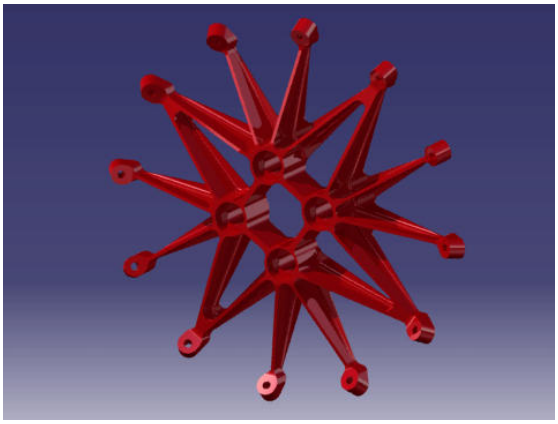

Figure 4. Aluminium wheel centre designed for carbon rims. *Image courtesy of M. Olsen*

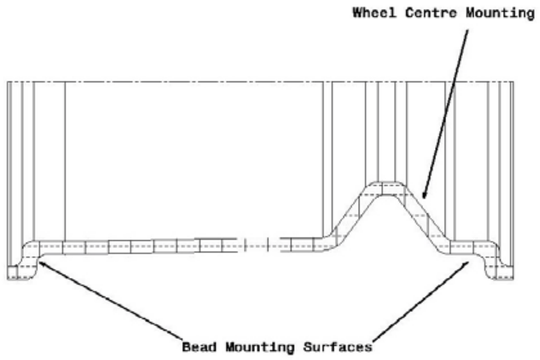

Figure 5. Cross section of the rim showing critical areas. *Figure 5 shows that the critical areas are located on both the inside and the outside of the rim, creating difficulties in moulding. Image courtesy of M. Olsen*

There are three identified critical surfaces for the composite rim, the wheel centre attachment face and the two tyre bead faces. These surfaces need to be dimensionally accurate and axially symmetric. If the wheel interface is out of round it will induce unwanted stresses to the wheel centre and the rim reducing the load carrying capacity of the rim. An out of round wheel will also result in wheel imbalance about the axis of rotation thereby oscillating vertical load with respect to rotational velocity. In addition, if the bead surfaces are not dimensionally accurate the bead will not seal on the rim properly and render the rim useless. The current wheels in use with Academy Racing run out of round slightly, as such they are hard to bead and come dangerously close to contacting the uprights, potentially damaging the upright and wheel if something such as a rock is lodged in between the two components.

VIII. Intended Design and Production

A. Design and analysis method

Dassault systems Flagship computer aided design (CAD) program CATIA® offers a composite design workbench that has a broad range of tools for designing composite parts. Beginning with a surface of the part composite layers can be built up to achieve the required properties of the components. This product description can then be moved into the analysis workbench and investigated using a 2D shell analysis with the composite properties previously defined. The order and make up of layers can be swapped easily to refine a design without having to change programs or re-setup the whole analysis when making minor changes. However, the CATIA® ELFINI® solver only uses 6 (Dassault Systems, 2009) of the 9 possible defining characteristics for composite materials. This is not as accurate, due to the assumptions made by the solver, as one that uses all nine constants to define the material properties. This makes using CATIA® ideal for the initial set up and rough analysis before verifying the results with a more accurate solver such as ANSYS®.

ANSYS® is a more advance and extremely powerful FEA package (Barbero, Finite Element Analysis of Composite Materials, 2008) that offers greater flexibility and accuracy than the ELFINI® solver. The ANSYS user interface is an inherent drawback, being more complicated to setup models and analyse them. The ANSYS® product PRE/POST® is a composite pre and post processor that has an intelligent user interface and still uses the ANSYS® solver, the script can also be saved before execution in order to be modified by the user for increased flexibility. This would be the ideal package to design and analyse the composite rim with but is not currently available at UNSW@ADFA. As such ANSYS® will be used to verify the ELFINI® results periodically throughout the design process, to ensure accuracy while still maintaining a high rate of work through the use of the CATIA® user interface.

However due to the complicated nature of the shape that the fabric will be placed over, the fibres will not be in the same orientation that the FEA package assumes them to be. As such the calculated results will not be accurate and cannot be relied upon. In light of this the rim calculations will be conducted by hand and the final product tested to prove its strength.

Conceptually, the forces imparted on the rim can be visualised as there are very clearly defined contact areas, this has driven the initial layup considerations of the rim. The drive/braking torsion loads are fed into the rim from the wheel centre and carried around the entire structure before being fed into the tyre through friction acting between the beads and the rim. These loads are best transferred through the use of a +/- 45 degree fabric (Rosato, 1997) so that they are balanced in both acceleration and braking.
The vertical loads are taken on the bead surfaces as a bearing load, in addition to the initial preload on the rim surface, as this takes the form of a hoop stress it is best supported through the use of a unidirectional tape forming a cylinder under these loaded areas (Christensen, 1979). The transfer of this vertical force from the beads to the wheel centre places the wheel body in bending and should be reacted at the upper and lower surfaces of the rim body with fibres running across the direction of bending, akin to the previously mentioned I-Beam. Finally, the lateral loads will be in compression and tension, through the surface of the rim in the axially biased fibres.

This initial conceptual design can be sized appropriately for the design loads and then analysed and further improved.

B. Manufacturing Methods

A number of different manufacturing techniques can be used to form a composite part. These all require the use of some sort of mould to determine the shape and ensure dimensional accuracy of the finished component. As the profile of the rim has both concave and convex surfaces it cannot be formed on a simple one piece mould. If it was it would be mechanically locked onto the mould requiring the mould to be destroyed to remove it. Possible solutions include collapsible or destroyable moulds, such as a plaster mould (McBeath, 2000). As the intent of this project is to use this prototype rim as the basis for a production run of 12 wheels, reusable mould would dramatically reduce the overall costs associated with the production of the wheel rims.

One further complexity is the inclusion of critical surfaces on both the inner and outer surfaces of the rim. This prevents the use of a single complex mould and then vacuum bagging to provide the required pressure for the curing of the matrix.

Using multi-piece matched metal moulds will give accurate parts, depending on the initial manufacture of the moulds, and allow the complex shapes to be removed from the mould without damage to either piece. This type of mould is able to be used in an autoclave if this is required by the matrix resin, they are also able to be reused, and as a result once they are manufactured there is no extra cost associated with their continued use (Dorworth, Gardiner, & Mellema, 2009).

The manufacture of a multi-piece metal, matched mould of this geometry requires the use, at a minimum, of a manual mill and a CNC lathe to ensure the correct profiles are cut. While it is a time consuming process it ensures accuracy and negates the need for a new mould to be manufactured for every part.

IX. Rim and Layup Design

A. Analysis of Current Wheel

In order to reverse engineer the properties of the current wheel sets to develop a minimum standard for the carbon fibre wheel, it was simplified to the geometry of a cylinder at its nominal diameter. This allows for the easy calculation of the maximum allowable hoop stress in the wheel, which can then be transferred to the carbon wheel ensuring that the minimum strengths of the wheel are not compromised. While this provides the overall strength of the wheels with radial forces it does not allow the stiffness to be determined as aluminium, the original material of the wheels, is isentropic whereas carbon fibre is not. To overcome this, a number of load cases were developed based on the forces experienced by the car in operation. These load cases were taken from the ADFA Racing design load cases and are the ones used for suspension analysis, they consist of both operational loads and crash loads, with safety factors defined in the document to ensure components are made with enough strength to be considered safe.

These load cases consist of cornering, braking and bump (vertical load) for the operational loads as well as bump combined with braking and bump combined with cornering as the crash loads. Curb strikes and large potholes are not considered as this would be outside of the expected conditions of autocross racing, the type of racing that FSAE is focussed on. As the load cases are presented in “g” forces they all have to be resolved for the cars weight, and weight transfer expected during the operation of the car.

The material the current wheels are made out of is 6061 aluminium that has been heat treated after manufacture to the T6 condition which has a nominal strength of 290 MPa and a modulus of elasticity of 68.9 GPa. The wheel has a nominal thickness of 1/8” = 3.175mm. As the radius (5” or 127mm) to thickness is much larger than 10, a thin wall approximation will be used to ascertain the ultimate strength and stiffness of the wheel. These parameters will then be used as the boundary conditions for calculating the material required for the carbon equivalent.

For this analysis the wheel will be broken down into sections that see similar loading methods and each section will have an equivalent amount of carbon fibre. The loadings and sections are as follows:

-Torsional loading of the entire rim for acceleration and braking forces. This load is imparted by the bead at the extremities and reacted by the wheel centre.

- Bending of the rim due to the weight of the car and any bumps encountered, this is imparted by the bead and again reacted at the wheel centre.

- Axial loading of cornering forces (meeting this requirement should require less material than required for the bending loading, but still needs to be considered)

- Radial force due to air pressure taken as a distributed load across the entire surface.

- Radial forces due to the bead of the tyre applied as a distributed load about the bead surface and the bead lip.

B. Composite System Selection
The composite system intended for the manufacture of the rim is developed by a Melbourne company, GMS Composites. Their product has been selected for a number of reasons, the primary reason being that they are able to supply the fabric and appropriate resin system for the cheapest price. In addition to this they will tailor the end product to our requirements with regard to resin content.

The initial design was originally conducted on an Advanced Composite Group 2x2 twill with their high Tg resin that was to be sourced through lavender composites in Sydney. However this material was $150 per sq metre and they were not able to supply a unidirectional cloth or tape in the same resin system. The GMS twill which is of comparable performance to the ACG product costs only $100 per square metre and their unidirectional High modulus fibre is $25 per linear metre and 100mm wide. Additionally the Tg of the resin system, EP-250, is no less than 175^{o}C and as such is more than adequate for use in the wheel rim.

C. Initial Design
Parameters:

l_{al} = nominal length of the Aluminium wheel = 0.1778 m (7”)
l_c = Nominal length of the carbon wheel = 0.1651 m (6.5”)
J_{Al}= Polar moment of Area for the Aluminium wheel (treated as a cylinder of 10”dia) = 3.8759x10^{-5}
I_{Al}= second moment of area for the Aluminium wheel = 1.9379x10^{-5}
G_{Al}=Shear Modulus of 6061-T6 = 26 GPa
E_{Al}= Young’s modulus = 68.9 GPa

The initial design concept uses only the twill fabric to react all of these forces. The fabric will be used in the 0/90 degree direction for axial and circrumfuncial loading and in the 45 degree direction for the torsional loading.

To calculate the 45 degree fibres required for the torsional reaction of the wheel the angle of twist equation will be used:

$$\varphi = \frac{Tl}{JG}$$

Where φ is angle of twist, T is torque applied, l is the length, J is the polar moment of inertia and G is the shear modulus of the material. As the rim is to have the same angle of twist for the same torque, the equation can be re arranged as follows:

$$\frac{l_{Al}}{J_{Al}G_{Al}} = \frac{l_c}{J_c G_c}$$

Using a typical value for shear of carbon fabric of 55 GPa, This is with the fibres orientated at 45 degrees to the loading direction, the required J_c becomes 1.7014x10^{-4} which is achievable with a thickness of 1.3mm. As the cured composite is 0.2mm this per layer, this gives a minimum requirement of 7 layers for the equivalent strength to the aluminium.

Treating the wheel as a simply supported cylinder held at one end with a nominal diameter of 10” will allow a carbon equivalent for the bending load imparted on the wheel due to weight. Using the simple bending equation:

$$\sigma = \frac{My}{I}$$

This can be rearranged to provide the following:

$$\frac{yF}{\varepsilon} = \frac{EI}{l}$$

Equating the y position, strain and “force” then allows a carbon equivalent to be established for the differing length, and young’s modulus. Equating the Aluminium properties and dimensions to the carbon properties (E = 64 GPa, and l_c) provides a required thickness of 16 plies. As the 45 degree fibres also contribute to the flexural stiffness (at 1.4 times the length due to the geometry therefore approximately 70% of the installed stiffness and there are 7 layers means that they are acting as the equivalent of 5 layers of the flexural fibres) this will allow the removal of five layers of the 0/90 bending fibres. This gives an initial layup consisting of 7 layers of 45 degree fibres and 11 layers of 0/90 degree fibres, providing 18 layers in total, with a thickness of 3.6 mm and a weight of 780 grams which is approximately 400 grams lighter than the current aluminium rim.

To confirm the carbon wheel strength in the radial loading case using the thin walled pressure vessel hoop stress equation:

$$\sigma = \frac{pr}{t}$$

Where p = pressure, r= Radius and t = thickness. This gives a maximum pressure of 7.19 MPa being applied radially to the rim before failure. Considering the 0/90 fibres initially, the minimum strength of these fibres is 771 MPa in compression and the thickness of the 12 layers is 2.4mm, this will allow a max pressure of 14.57 MPa which is twice that of the aluminium rim and as such not going to fail before the original in this load case.

Considering the lateral load case the max stress condition is going to occur as a uni-axial loading situation. Therefore:

$$\sigma = \frac{F}{A}$$

The maximum stress that the aluminium rim analogue can support is 714 KN along its axis. In the carbon equivalent, again considering the 0/90 fibres provides the capacity for 1850 KN. In this case the carbon rim satisfies the strength requirement established by the aluminium rim. The plies will be ordered such that there is a 45 degree capping ply against the mould surface, then 5 plies of 0 degree fibres, then 5 plies of 45 degree, then 6 plies of 0 degree cloth, finished with a single ply of 45 degrees as a capping layer. Two more narrow layers of 0 degree cloth need to be applied at the location of the bead bump for grinding to the appropriate shape.

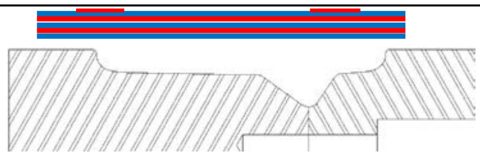

Figure 6. The ply order of the original design. *Blue represents 45^o twill and red 90^o twill.*

D. Revised layup design

The quantity of fibres running circumferentially around the rim was in excess of what was required to be considered equivalent to the strength of the aluminium rim, as they were sized by the stiffness provided in the axial direction for equivalence in bending stiffness. This reduced the efficiency of the structure and more importantly increased the price per part with no substantial gain. Considering that these layers are difficult to lay onto the mould and are not an efficient use of material they could be replaced with unidirectional cloth or tape.

This would allow a more tailored approach to the design of the wheel, reduce the cost per part, and improve the layup of the plies to improve the end product.

Using a high modulus 300gsm carbon fibre tape (tensile modulus of 620GPa and a flexural modulus of 300 GPa) with a nominal thickness of 0.32mm requires only three layers (rounded up from 2.1) of material to provide the same bending stiffness as the original aluminium rim. With the additional stiffness provided by the 45 degree fibres this requirement can be reduced to two layers of the 300gsm tape running axially along the wheel. Again to ensure the uniaxial loading of the rim it will be compared to the aluminium rim requiring a minimum of 714KN. The unidirectional carbon is able to support a load of up to 1018KN, satisfying the uniaxial loading critea.

To ensure that the rim can still absorb the pressure imparted by the air in the wheel one layer of the unidirectional tape will run circumferentially around the rim. This will allow the entire rim to be able to support a pressure load of up to 286 psi (1.97 Mpa) as the beading pressure normally does not exceed 40 psi (as dictated by the tyre manufacture as the maximum beading pressure). This satisfies the strength critea for highest air pressure load.

As the lip of the rim and the beading section will see a much greater load due to the stretching of the tyre over them and the direct application of the vehicles weight through the bead, this area will be developed to the same hoop loading capacity as the aluminium rim. Using the hoop stress equations listed above and the specifications of the unidirectional tape the required thickness of tape is 1.1 mm (between three and 4 plys) as there are already a considerable thickness in these areas from other carbon fibre (seven layers of 45^o cloth , three layers of 0^o tape and one layer of 90^o tape) only two more layers of 90^o tape will be added to these areas to bring the total number of 90^o plies to three. This rim has an expected weight of 620 grams providing more than 500 grams of weight saving per corner.

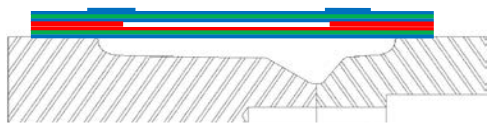

Figure 7. The ply order of the revised design. *Blue represents 45^o twill, green 0^o UD and red 90^o UD*

The plies will be ordered such that there is a 45 degree twill capping layer, then one of the two 0 degree tape layers followed by the 90 degree tape layer over the entire rim, then the two 90 degree tape layers in the beading areas and the lip of the rim. Five 45 degree twill layers are then to be placed on followed by the final 0 degree tape layer and the whole assembly covered by a 45degree twill capping layer. Again two more narrow layers of 0 degree twill cloth are required in the place of the bead bump for shaping after cure.

E. Rim Geometry Design

The contour that the rim profile was designed to followed two major critea, the design standards for tyre beads and the packaging requirements of the FSAE vehicle. The main need that drove the rim profile was that of the tyre bead being retained while the wheel was at the low race pressure of 10 psi. As discussed earlier the current rims that the team uses does not include a bead bump and after prolonged use at race pressure the tyre begins to roll off the bead, posing a safety risk for its continual use. To combat this problems the Tire and Rim Association 2006 rim section data was used to develop the beading geometry for the wheel. As the rim section data did not provide a dimension for a 10" wheel the dimensions were extrapolated based on the data provided.

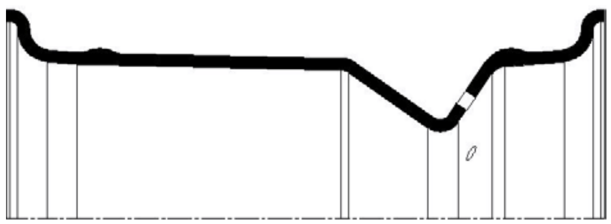

Figure 8. The final rim profile showing the bead bumps critical for tyre retention.

The second driving consideration in the development of the wheel geometry was maximising the packaging room inside the wheel for the uprights, hubs and brakes as well as the suspension arms.

F. Bolting Calculations

As the rim will be mechanically fastened to the centre, the number of bolts and their quantity need to be checked for strength to ensure that they will be suitable for the job. The only calculations that will be conducted here will be the shear case that is created by a rotational acceleration of the wheel. The vertical and axial load cases are not held purely by the fastener because of the angle that the wheel and wheel centre mate on. This makes the calculations much more complicated as they consist of through plane loading in composite materials. These joints should be checked through the use of proof loading of the initial wheel. The original design by M. Olsen called for 12x 3/16" hiloks to be used to secure the two parts together. A steel hilok pin has a minimum sheer strength of 95ksi or 655MPa. This translates to an allowable sheer capacity of at least 11000N per fastener.

The wheel centre consists of two different types of spokes, one is the triangulated two finger spoke and the other is the cantilever one finger spoke. From simple visual observation the triangulated spokes are going to be stiffer and as such carry more load than the single spoke. To confirm this an analysis was conducted in CATIA to ascertain the stiffness difference of the two. A nominal load of 1000N was applied to each of the spokes as though a rotational acceleration load was being reacted. The triangulated spoke deformed 0.5mm while the cantilever spoke deformed 35mm. Due to the stiffness ratio being in the order of 70 to 1 all of the bolting calculations for the rotational acceleration of the wheel will be conducted with only 4 fastening locations..

The torque from the front brake disc at 1.6g is approximately 352 Nm, this value takes into account the increase in weight and therefore the increase in friction cause by the deceleration. Reacting this torque at a distance of 0.1m over four bolts provides a shear load of 880N per bolt. Which is less than $1/10^{th}$ of the capacity of the pins.

As the bolted joint is not near an edge of the material the e/d and the w/d values indicate that the joint will fail in a bearing nature rather than a shear our or tension failure. The optimal allowable bearing stress would be the compressive yield stress of the material and the clamping force applied to either side of a bolt reduces the instances of micro buckling and increases the allowable stress in a composite bolted joint. From this the allowable bearing stress will be conservatively taken as 70% of the maximum compressive stress of the composite material because this can be achieved with a minimum of 3 MPa of clamping stress. The only layers that will be considered will be the 45 degree fibres as they will be reacting the majority of the torque and the load transfer from friction will be ignored. As such 70% of the transverse compressive strength in the 2x2 carbon twill is approximately 540 MPa.

The 45 degree fibres have a thickness of 1.4mm and the 3/16" bolt a width of 4.76 mm, to compensate for the fact that the stress from bearing is not evenly distributed the calculation will be performed at only 75% of the holes cross-sectional area providing an equivalent width of 3.5mm. With a load of 1760 N (double the maximum load that the pins will see) this equates to an equivalent stress of 352 MPa. As this is within the allowable load the bolted joints are sufficiently strong.

G. Corrosion Protection

As discussed earlier in this thesis there is a strong need to ensure that the prevention of corrosion is considered in the design of the rim to ensure that the parts have a long service life. The simplest solution to prevent corrosion would be to use non reactive materials in the assembly, such as a titanium wheel centre with the carbon rim. Due to financial restraints this is not possible and an alternate solution is required. Sufficient protection from corrosion can be achieved by simply using a protective barrier between parts that will either insulate them and prevent a galvanic cell from occurring, or in the case of aviation bolts act as a sacrificial anode.

The Hilok pins that will be used to fasten the wheel centre and the rim together are cadmium plated for corrosion protection of the steel already. As the cadmium is more active than the aluminium it will act to protect this material too. Additionally the intended anodising on the aluminium will act to prevent the corrosion of the wheel centre too, creating a hard oxide layer on the surface that reduces the occurrence of corrosion in the parent material.

The final tool that will be used in the prevention of corrosion is very simple. Placing a small amount of non conductive material between the two materials in effect breaks the circuit that would cause the corrosion. Vinyl stickers can cut to almost any custom shape for very little money. Having a sheet of stickers cut so that they can stick to the contact section of the rim will provide and insulating barrier that is low cost and out of sight as to not detract from the appearance of the rim.

H. Mould Design

Initially the mould was intended to be a multi piece matched mould for its high quality surface finish and the reduced need of post cure operations. During the initial design analysis of this concept the costs involved were becoming prohibitive. The material required for the centre section was valued at approximately $1000, the external sections would require at least double this quantity of material and considerably more machining. Further to that, the mould would weigh approximately 60Kg which would make handling and heating in an autoclave or oven extremely difficult. In light of this it was decided that the use of a two piece internal mould with a vacuum bagged external surface. This method of manufacture requires considerably more consumable materials per manufacturing operation, however the FSAE team is only conducting a limited production run and the costs associated with the consumables will be less than that associated with a matched mould, if the design was being produced in a larger production run it would be more economically viable to used the matched moulds as there would be less time required for setting up the bagging and less consumables.

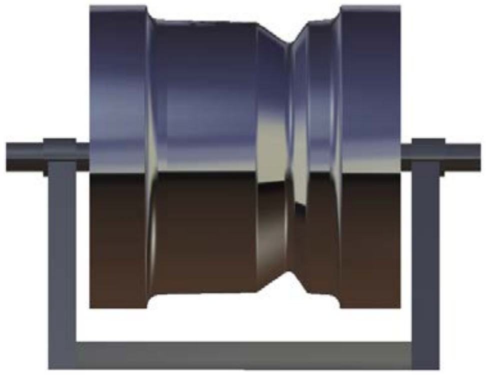

Figure 9. The mould and stand assembly

The geometry for the mould was developed from the rim profile geometry. Once the rim profile had been established and the thickness of the fibre laminate was determined the mould geometry could be developed. In CATIA the rim profile was turned into a construction part and then a second profile drawn that was 3.6 mm smaller in radius than the original profile. The bead bump section was removed and replaced with a flat section as it would have physically locked the part onto the mould if it was included in the design. As the bead bump is a critical part of this design it will be ground into the finished rim surface after cure to ensure its accuracy and that the tyre will seal on it.

The mould its self was designed to be easy to work with, as such it requires access over the whole moulding surface and can be moved with relative ease. To facilitate this the mould was designed with a stand at the same time to allow access around the mould by simply spinning it on its axis and providing lifting points that do not compromise the cleanliness of the surface. This stand was initially designed and manufactured to be relatively small and had very little (45mm) clearance between the mould and the bottom stabilising legs. This lack of clearance meant that the materials involved in vacuum bagging were being caught and potentially damaged as the mould was rotated to reach other sections of it.

Figure 10. The mould after manufacture and polishing

The mould is supported on the stand via a 1” tube that runs through a hole in the mould that extends from one side to the other. These holes aid in the assembly of the mould and allow further jigging for subsequent operations on the mould. The assembly of the mould is improved by locating both parts on the central tube before mating them together, this allows them to already be axially aligned and reduces the chances of the mould binding due to an off axis installation. The central hole and spigot recess allow a jig to be attached that will facilitate the drilling of the holes required in the rim for attachment to the wheel centre.

The mould is a two piece split mould, with the split located at the lowest point of the mould so that the part does not become mechanically locked onto the mould. In the small half of the mould there is a spigot which mates into the large part of the mould to ensure concentricity during assembly and use. The mould halves are clamped together by 4 x 12mm bolts evenly spaced around the mould. These bolts have through holes in the smaller half of the mould and tapped holes in the large half of the mould to clamp the two halves together. There is a minimum 1 degree of draft angle included on the long sections of the mould with to facilitate part removal. The sections of the mould that are parallel to the direction of removal are kept to a minimum (approximately 30 mm total) and are only included out of necessity for the Department of Transport (US) standard.

In order to facilitate the separation of the mould there are a further 4 bolts located on the small half of the mould, they are evenly spaced in between the clamping bolts. These bolts screw into a threaded section in the small half of the mould, and wind against the bottom half of the mould. When these bolts are tightened they push the two mould halves apart.

I. Fabric Testing

As the rim consists of a double curvature, an extremely complex shape for cloth to drape around, initial testing of the drape of the fabric needs to be conducted. In order to do this a small section of the rim mould was machined out of balsawood on a 3 axis CNC router. This model was made out of nine pieces of wood and glued together, the wood dimensions were limited by the fact that the router is primarily used to machine "F1 in schools" cars and the set up was not allowed to be changed. The model approximated 140 degrees of the rim surface and included one bead section, the rim mounting area and approximately 60mm of the flat area on the rim profile.

Figure 11. The balsa wood wheel model for drape testing.

The nine pieces of wood were glued together then any gaps were filled and the model was sanded smooth. 285gsm glass 2x2 twill was used as the test fabric on the advice or Dr Rik Heselhurst. From this testing it could be seen that the fabric would drape around the surface while dry in for up to 1/3 of the wheel circumference. As such the twill fabric would be useable in the manufacture of the wheel.

X. Post Cure finishing

A. Post Cure inspection

After the finished product has been removed from the mould the rim requires inspection to ensure that it is structurally sound before any further operations are carried out on it. As the rim is a very thin part ultrasonic inspection will not work correctly and alternate inspection operations need to be conducted to ascertain the quality of the layup. Initially a visual inspection is to be carried out, this inspection is to look for any surface voids, air bubbles, dry fibres or other imperfections. Once the rim has been inspected for visual defects a tap test should be conducted to in an attempt to find any delaminations in the material. This is then to be followed by inspection through a thermal camera with a heat source being directed at the rim. Discrepancies in the temperature distribution across the rims surface are indications that the thermal path of the material is being interrupted in some manner and could be an indication of a delamination.

These tests should be conducted with an experienced NDI person present to ensure the accuracy of the tests. If the part passes all of these inspections then it is suitable for further finishing operations in preparation for use.

B. Machining

Due to the nature of the vacuum bagging process the surface finish on the outer surface of the rim will have small depressions, raised sections, and possibly resin rich out of round areas. The free ends of the wheel will also be of a ragged unfinished nature of varying thickness and protrusion from the mould. In order to fix this and make it suitable for the beading, and sealing of a tyre post moulding operations are required.

There are a number of different methods that can be used for the post machining of composite parts. Much in the same way as a metal composite parts can be drilled, filed, cut, ground, milled and turned. However special consideration is required when machining composites due to the unique nature of the materials. Because of the makeup of fibre reinforced composites they can suffer from a number of problems during machining operations. These defects in the final part include but are not limited to delamination, cracking, fibre pullout and burning. In addition to this the machining of composites can pose health concerns to the machine operators and nearby personnel.

The perfect example of composite induced health effects is asbestosis, where by the machining of asbestos based materials generates particles that were small enough to get into the deepest section of a humans lungs and permanently lodge there. This causes severe irritation, reduction in lung function and eventually leads to death. While a graphite and epoxy composite generate an annoying dust they are not deadly as the particles are too large to reach the depths of a humans lungs. The particles are non toxic and are listed as not carcinogenic. It is good practice though to use the correct PPE and an appropriate dust extraction system as the dust can make a person itch and cause coughing as well as the production of excessive mucus in an attempt to filter the dust from the inhaled air.

Due to the toughness and abrasive nature of composite materials conventional cutting tools tend to wear out faster than they would when machining metals. This has prompted the use of diamond coated tooling in manufacturing of composite parts. Diamond being one of the hardest materials on earth wears at a slower rate than carbide or steel does thus retaining a cutting edge that is more effective for longer. However diamond tools are significantly more expensive than the conventional tooling due to a more intensive manufacturing process and a lower production count. This being said steel or carbide tooling can still be used though extra attention is required to ensure that the tools are sharp enough during operation.

For the wheel being designed in this thesis there are three primary machining operations that are required. These are the drilling of holes for the wheel centre to attach to, the finishing of the outer surface and bead surface so that the tyre will seal and the cleaning up of the edges of the part.

The wheel requires the drilling of 12 equally spaced holes about the previously indicated mating face to join the wheel centre to the rim. These holes are then required to be reamed to 3/16" diameter so that they have a bearing critical fit with the fasteners , Hilok pins, to reduce the likely hood of fretting inducing a failure in the material. A 13th hole of 19 mm is also required for the air valve to occupy. Using a standard drill that is shaped to cut steel or aluminium, ie a 118^{o} tip angle, will try and push the layers of the composite apart and cause delaminations in the material. To overcome this a drill can be sharpened to a 60^{o} angle to reduce the through plane forces on the laminate. Alternately a "w" point drill can be used, this drill has a centre point and then two tips at the major diameter, it works on the theory that the two outside points will cut through the material and only apply a through plane force to the waste material, that way even if the waste material begins to delaminate because the edges are cut the delamination cannot travel into the parent material.

In order to drill the holes in the correct position they are required to be match drilled using the wheel centre as a jig. As the mating surfaces of the centre and the rim are conical they will self locate. To aid in the location and securing of the centre for drilling the part should be placed back on the large half of the mould and the wheel centre then attached to the wheel centre drill jig, drawings are included as an annex, and placed into the locating recess. A length of threaded rod should then be placed through the centre of the mould and the appropriate washers should be placed on both ends so that as the nuts on the rod are tightened the wheel centre and mould are both drawn against the part. The conical faces will then locate the centre in relation to the rim, this concentricity is still required to be checked by measuring the distance between the edge of the wheel centre and the edge of the rim. The holes should all be drilled and then both the rim and the centre reamed in this position so that they line up as exactly as possible. The thirteenth hole for the valve is then to be drilled in between two of the narrow arms on the wheel centre. Due to their stiffness these arms react very little axial torque from the wheel and as such the load over the valve hole will be much smaller than if it was in close proximity to the triangulated arms. The relative orientation of the centre and the rim needs to be marked so that and individual inconsistencies don't prevent the two parts from mating later on. The whole assembly is then to be disassembled and the centre permanently installed. When installing the centre each of the holes require some high temperature sealant (commonly known as "gasket goo") applied around them before the insertion of the Hiloks to ensure an airtight seal, the Hilok is to be then pushed through the sealant and into the wheel centre. This will prevent air from leaking out of the rim and causing the tyres to deflate.

The edges of the part require trimming to size and then smoothing for finishing. These operations are required so that the material does not catch on, and cut into, the tyre, to remove to excess weight that the un-required composite has and to improve the aesthetic appearance. The primary reason for cleaning the edges is so that the tyre is not damaged during the mounting or removal processes, as any sharp edges can cut into the rubber bead, this will prevent the tyre sealing against the wheel rendering it useless.

Using a diamond cutting disc on a saw table the edges need to be roughly cut back, leaving approximately 1 mm of extra material on the edge for final finishing. This method uses abrasion to remove the material and significantly reduces the occurrences of delaminating or fibre pullout. The edge should be ground to the correct size when the bead is ground, this will allow for a smooth and consistent edge. After the edge has been ground they should then be rounded by hand with sand paper so that the tyre has a lower probability of catching and causing damage to either the rim or the tyre.

The bead seating area is critical to the tyre sealing and staying on the rim and the finish that will be present from the vacuum bagging surface will not be smooth or consistent enough for the try to seat correctly. To make this area take the correct shape and have the appropriate surface finish a grinding operation is required. The rim should be placed back on the mould and the entire outside surface should be lightly sanded to remove any high spots or resin rich areas, The surface finish is not required to be perfect, but it is required to be relatively smooth and consistent with no deep groves or high sections. Anything that protrudes from the surface should be sanded back and any holes should be filled with some "Plasti-Bond" a two part plastic putty and then sanded smooth. This will ensure that the tyre can slide along the rim so that it can get to the beading area without being caught on anything.

Once the wheel centre is installed the wheel can be mounted on a spigot which can then be used to hold the wheel in a lathe to be ground with a tool post grinder, or other grinder that allows axially symmetric parts to be ground. Composite materials can be ground, but some extra precautions are required when doing this. Firstly there must be an extraction system to collect the dust so that it is not inhaled by the machine operator or nearby people. Secondly a grinding wheel designed for steel straight from the factory is not adequate for the grinding of composite materials. The matrix material will clog the wheel preventing proper material removal and cause localised heating of the composite material, possibly burning it to the point of losing mechanical properties. The can also cause an imbalance in the grinding wheel and if the clogged material is heavy enough cause the wheel to disintegrate creating a hazardous condition for the operator.

The recommended way to grind composites is using a wheel that has been dressed to be very open so that that it is hard to clog (Lubin & Peters, 1998). Dressing is the process of cutting into the face of a grinding wheel using a diamond tipped tool to remove material. This can be used to shape the wheel, remove clogged material and open the cutting surface. Flexovit (an abrasives company that make grinding wheels) advise that the material that the wheel is made out of does play a significant role and any standard grinding wheel can be used. They also recommended that if this operation was being conducted for a large production run that a diamond coated wheel should be made to the correct dimensions to remove the problem of clogging and wheel shaping. This solution was not financially viable for the limited production run that will be conducted for the Academy Racing Team.

The grinding wheel profile consists of a 20mm wide grinding wheel with a 6mm radius on both edges. The bead section is to be ground at a 5 degree angle to the axis of rotation (with the wheel angled towards the centre of the rim) until the maximum diameter is at 254 mm. The bead bump section of the rim is to be ground flat to

255.2mm dia. This section of the rim is then to be inspected and hand finished to remove any sharp edges that could catch on the tyre bead.

XI. Test layups

A. Layup 1

The first layup of the wheel was intended to fulfil a number of aims none of which were to make a final part, but with the general goal of practicing the layup and working out the tricks to make the part work. As such the part manufactured was not the full thickness that the final parts will be, it was also made out of fibreglass using a wet layup as the material costs of the pre-impregnated carbon is to prohibitive to conduct practice runs and make what will essentially be scrap parts. The aims of the layup could be divided into three broad areas; the preparatory work, the layup and vacuum bagging and the post cure work.

1. Preparatory work

Before any work with the composite materials could begin the mould had to be assembled for the first time. When attempting to fit the mould for the first time it was apparent that the tolerance on the two mating parts of the mould were too tight and required some adjusting by sanding the inside of the locating recess with some scotchbrite. The original drawing called out for both sections to have the same major dimension with a tolerance of $X^{0}_{-0.02}$ on the spigot and the recess had a tolerance of $X^{+0.02}_{0}$ this essentially allowed the part to be either size for size, which would have made the fit a "locational clearance" fit or the gap may have been as large as a "sliding fit" at 0.04mm gap. As the mould is made from aluminium it would have a high chance of binding with any slight miss alignment at these distances and destroying the locating surfaces resulting in costly repairs the tolerances should have been in the order of $X - 0.02^{0}_{-0.02}$for the spigot and $X + 0.02^{+0.02}_{0}$ to ensure a close running fit. As such the locating recess was expanded through some sanding until the two halves of the mould could be assembled easily, with no noticeable slop. The mould mating surfaces were then liberally coated in high temperature nickel anti seize and assembled.

After the assembly the mould was cleaned with acetone. Initially this was done using paper towel and wiping over the surface removing any contaminants with the solvent. Once the paper towel was showing very little signs of contaminants the mould was wiped over with clean white cloths to show the slightest traces of contamination. This process was continued until there was no noticeable contamination on the cloths, at which point a strip of masking tape was run around the two edges of the mould to prevent any wax from affecting the sealing of the vacuum bagging tape that would later be applied there. The mould was then waxed 4 times using a fibre glass release wax, this is a product designed to fill in the microscopic cracks on the surface of the mould to prevent any mechanical locking of the resin into the mould surface. This wax is applied and then allowed to harden for a few hours before being buffed off. While the wax was hardening the mould was covered to prevent it from accumulating any dust from the workshop area. After the surface preparation of the mould was complete it was moved to the composites lab.

The template for the fibre material was developed from a net projection of 140^{o} of the moulding surface, this would allow each fabric section to have approximately 10mm of overlap on the neighbouring sections in an attempt to compensate for not having continual fibres running around the entire part. This template was transferred onto an aluminium sheet and cut out so that it could be placed directly onto the fibre and cut around. Two test sections of fabric were then cut from 285gsm 2x2 twill glass, these sections were at 0degrees and 45degrees to confirm the drape on the actual part. While testing the drape the difference in fibre shear from the different orientations was apparent. The 0 degree fibre appeared to conform well to the surface with only some slight deviation from the intended coverage in the lowest point of the mould (consequently some material was removed from this area for the sheets that were later cut out for layup). The 45 degree fibre showed considerable changes to its intended shape, the centre of the sheet shortened as the fibres moved and did not cover from one side to the other. To rectify this the 45 degree sections had approximately 15mm added to each end. In total four layers of fabric were cut, 2 at 0 degrees and 2 at 45 degrees.

To improve the speed at which the mould could be vacuum bagged once the part was layed up all of the required materials were pre-cut. For the vacuum bag setup the following materials were used; peel ply, perforated release, breather cloth and then the vacuum bag. The all of the cloths were intended to run circumferentially around the part and to try and avoid bunching, subsequently bridging, the peel ply was cut into strips so the radius changes along the part would cause minimal disturbance to the laying of the fabric. The vacuum line was fed into the part through an extension section so that the sniffer (vacuum port) would not leave any flat spots on the rim surface.

The fabric was weighed, each layer weighed approximately 70 grams and then the resin was prepared at a ratio of 1.2 grams of resin for every gram of fabric. Additionally some extra resin was prepared to be used to dab down any fabric that was not conforming to the moulding shape and to fill in voids. This resin content was particularly high, but chosen as a conservative approach to the first layup. The resin used was West Systems 105 epoxy with the 206 slow hardener to ensure sufficient working time. This resin has a minimum working time of 90 minutes and a maximum 16 hour cure time.

2. Layup

Enough resin for one layer at a time was mixed so that it would not harden in the pot. The first layer of fibreglass was pre impregnated with resin by sandwiching it between two sections of release film and forcing the resin through it with rubber squeegees. This ensured that the fibre was sufficiently wetted. A thin layer of resin was painted onto the surface of the mould in an attempt to reduce pinholes against the tool and then the first layer of cloth was added, one third at a time. The narrowest section of each ply was lined up with the deepest section of the mould and then was worked into place through the use of fingers and brushes. The best method was to ensure that the ply was forming to the deepest section of the ply and then begin pushing the rest of the ply down working from the centre out and supporting the last area that was done while doing the next section. The second layer of glass without being pre-impregnated was applied to the first layer and then the resin was painted onto it, while applying the resin the brushed were used to remove any air bubbles any push the layer into the contours of the mould. This same process was repeated for the third and fourth layers. In an attempt to balance the layup the ply construction was $[45/90]_s$. There was a noticeable difference in the formability of the two different layers. The 45 degree layers conformed to the mould surface with relative ease while the 0 degree layers took considerable more working and even then they would shift significantly and lift if they were slightly disturbed. This problem was caused by the fibres running perpendicular and parallel to large changes in radius on the part. As the parts radius changes the axial fibres are required to splay and contract, as the radial fibres will not stretch or contract and the whole cloth is woven they two fibres work against each other and cause the fabric to pull up from one section as another is pushed down. With considerable working the fabric will conform to the surface however the fibre orientation can be significantly disturbed during this process. This issue is not as prevalent in the 45 degree fibres, they do not run perpendicular to changes in radius and as such they will shear slightly in a scissoring motion allowing them to conform to the contours easier than the 0 degree sheets.

Once all four layers had been applied the tape was removed from the edges of the mould and vacuum bagging sealant tape was applied (with the backing still left on the outside). The peel ply was then wrapped around the part against last layer of the glass. The perforated release was then wrapped around the peel ply followed by the breather cloth and then the vacuum bag. The bag was pleated so that it could pull down into the deeper sections of the wheel. The vacuum pump was then applied and turned up to the maximum suction, as there was an excess of resin in the cloth and this part was not structural there was no need to try and develop a breather /vacuum combination for controlled resin content.

The application of the breather and release materials took longer than was expected due to poor preparation. While they were cut to the correct sizes the edges were not square nor particularly straight, as such modifications to the materials had to be conducted as they were being applied. This was particularly prevalent with the actual vacuum bag, when it came time to join the two ends together they were of different sizes and required extra folds and taping to make sure that they would seal. All of this took extra time and by the time that the vacuum was applied the resin that was left in the pot from the first layer was beginning to gel. This would inhibit the potential for the resin to flow and any excess to bleed out. This shows that it would be impractical to layup 18 layers in this manner and still be able to apply the vacuum to draw it all together for cure unless an extremely slow hardener was used. After the vacuum was applied the line was disconnected to see the quality of the seal created. Within 30 seconds the bag was loose enough to move by hand, indicating that there was a significant vacuum leak in the bag or seals. However this leak was silent and could not be found.

3. Post Cure Work

The part was left for approximately 20 hours before being de-bagged, upon inspection there appeared to be significant resin bleed which was too be expected due to the resin rich formulation used. The vacuum bag and the breather cloth were able to be removed easily, however perforated release and the peel ply would not release from the deepest part of the wheel. Upon a closer inspection the materials appeared to have wrapped back on themselves in some cases and to voids completely filled with resin, making the sections mechanically locked onto the part. This extra resin also made it difficult to inspect the last layer of glass for any deficiencies in following the path of the mould in this area. A different method of laying the release and peel ply will be used in further layups in an attempt to solve this problem.

The mould separated in half as was originally intended by removing the clamping bolts on the mould and then tightening the separation bolts. The separation was loud as the resin let go from the mould surface, but freed the top section with no damage to the part or the tool. As the GFRP is relatively see-through where the part had released from the tool was apparent by an opaque section extending from the free edge of the part to approximately half way down the mould. So the release of the part could be tracked this edge was marked with a permanent marker line on the part.

The first attempt to remove the part from the mould relied on a brute force approach. Two sections of 1" steel tube were clamped about the narrowest section of the part and then their ends were supported such that the tool was unsupported. A ratchet tie down strap was then threaded through the centre hole in the tool and secured at both ends so that when it was tightened it would attempt to pull the mould out of the part. This setup was loaded until there was noticeable deformation on the inside moulded surface of the part. This attempt at separation succeeded in gaining approximately 5mm more of released part, however damaging the part in the process by plastically deforming the section of the part where the tubes rested against.

The second attempt at releasing the part made use of an oven in the civil engineering department set to 50^{o} C as the Tg onset temperature of the epoxy is only 52^{o} C in an attempt to make the mould expand and break the bond. This method achieved no gain in released section, however the damaged section of the part appeared to have become less prevalent, presumably as the material softened due to the temperature increase it moved back into the original cure condition.

The third and successful attempt to separate the part from the mould made use of the difference in CTE of the fibre glass and the aluminium mould. The part and tool were placed in a standard household freezer set to the coldest setting, around -18o C and left for 16 hours. When the part and tool were removed the part in some areas had released all of the way along the mould, however some areas still had not released all of the way and the moulds weight alone was not enough to cause this bond to break. A heat gun was then used to gently heat the GFR. The growth of the released area could be physically seen to follow the path of the heat gun and after only a minor application the part lifted off the mould.

Inspection of the inside of the part rereleased some resin rich areas and some air bubbles that were presumably not able to escape due to the resin beginning to gel before the vacuum was applied. Aside from the imperfections that were caused by the use of a wet layup the GFRP appeared to follow the contours of the mould faithfully without lifting off around the relatively sharp corners. Additionally the inside surface of the part was smooth and accurate, providing a nice surface for the wheel centre to mate on, as was expected from the tool type. The external surface of the part was very rough, everywhere that there had been a fold in the release ply or peel ply there was a resin rich bridge that would required significant finishing.

When the part was removed from the mould it weighed 510 grams and after roughly finishing the edges of the part it weighed 440 grams. With the resin content that was used and no bleed the un finished part should have weighed in excess of 580 grams showing the significant quantities of resin bleed that had occurred.

4. Summary of Layup 1

The first layup of the wheel revealed the how complicated the manufacture of the wheel would be with the double curvature geometry. The 2x2 twill at a 45 degree angle worked onto the surface well, however the 0 degree fabric was much more difficult to work with, though not impossible. The experiment showed the difficulty associated with the requirement to work extremely fast so that the part does not begin to gel before vacuum is applied. The wet layup also gave rise to resin rich areas and voids that could have been avoided through the use of a pre-impregnated material. The lack of attention in preparing the bagging materials slowed down the application of the vacuum and caused significant quantities of peel ply and perforated release to be stuck to the mould making the deepest section of the mould (where the wheel centre is to attached) relatively useless. The materials used for the bagging require better preparation for future layups.

Figure 12. The first layup all glass rim after the edges have been trimmed

The removal of the part from the mould was best done by freezing the assembly and working the part off using heat guns.

B. Layup Two

As with the initial layup, the secondary layup was not intended to manufacture a final part but rather to test the layup procedure and mould to ensure that it would work. This layup consisted of three global layers and a localised fourth layer in the beading area. There was a bottom layer of 45o 285gsm 2x2 glass twill, a middle layer of 0^o 300gsm carbon tape and a capping layer of the 45^o glass twill. There were some tows of carbon also wrapped around the beading area. Again this was conducted as a wet layup and room temperature cure. As the majority of the procedures were the same as the first layup, only the differences will be discussed in the following paragraphs.

1. Preparatory work

After the mould was assembled there were noticeable sections that resin had bonded to, particularly the edges where the tape had been and had not been fully waxed. A number of different methods were tried to remove the resin, being scraping, heat gun, the use of acetone and the application of a blow torch. Eventually the most successful method was to use 3M paint stripper. Applying a small amount of stripper onto the resin and letting it set made is soft enough that a wooden tongue depressor could be used to remove the excess resin. The whole mould was then cleaned and waxed as per the first layup.

Again the vacuum bagging materials were prepared before the layup was started, this time the materials were properly measured and cut square in an attempt to reduce the time to get the vacuum onto the part. Additionally the peel ply was cut into 50mm strips with the intention of placing it parallel to the axis of rotation in an attempt to reduce the occurrence of it becoming permanently attached to the mould. Two layers of breather/bleeder cloth were also prepared, one like the peel ply in 50mm strips to be placed parallel to the axis of rotation, and the final layer to be wrapped around the entire mould. The vacuum bag was cut to be 800 (across the mould) x900 mm (around the mould) so that three large pleats could be included for each of the major changes in diameter. In order to get more pressure in these areas and a better finish on the surface.

The template for the 45^o fibres was changed slightly to taper in more at the smallest radius section of the mould, six sections enough for two layers were cut out. 17 sections of the 50mm tape were cut to be approximately 190mm long. The resin was then prepared at a ratio of 1:1 to try and reduce the final resin ratio on the part.

2. Layup

The first layer of glass was manually pre-impregnated with the resin, slightly less than the full amount prepared was used. The glass appeared to be fully wetted. This was then applied directly onto the mould without painting an initial layer of resin on the surface. With the lower resin content and no resin already on the mould the glass appeared to drape better and had less of a tendency to pull back off the surface. The first layer was worked into place primarily with gloved fingers and then with paint brushes. There was too much overlap removed in the modification of the template, with only 3-4mm on each side overlapping in the deepest portion of the mould.

The first strip of carbon tape was initially applied dry and then wetted out using resin painted on with brushes. This took a considerable amount of time to wet the tape out enough for it to become pliable. The subsequent sections of tape were wetted out prior to going on the mould through the pre-impregnation method. These were then applied to the mould and pushed into place using fingers and brushes. As with the glass cloth in the first layup the best method to apply the carbon to the part was to located it in the deepest section of the mould first and then work it towards the outside. The reduced the occurrence of the carbon pulling up from the previously worked on area and reduced the time required to lay each strip. Approximately and extra 20 grams of resin was required to fully wet out the carbon strips.

Figure 13. Peel Ply application in layup two. *The change in peel ply application that significantly improved the mould surface finish*

Once all 17 layers of the carbon were in place a tow of carbon was wrapped around the beading sections to represent the unidirectional cloth that was intended to be placed there on the final part and to assist in holding the carbon tape in place, which appeared to not be fully wet out despite the obvious quantities of resin on the surface of some strips as some sections were not as pliable as others. The final layer of glass was placed onto the surface dry and wet out using brushes, with the addition of this layer and the working in of resin the carbon strips begun to conform to the mould with greater ease.

The bagging materials were then added, the part sealed and a vacuum applied. The leftover resin in the mixing cups had again begun to gel by the time that the vacuum was applied. In order to test the seal of the vacuum bag the line was removed, within one minute the bag could be easily shifted by hand indicating that the vacuum had greatly reduced. This was better than the first layup but still not ideal, again the leak could not be found.

3. Post Cure Work

After leaving the part for 20 hours the vacuum and the bagging materials were removed. The bleeder cloth still showed signs of bled resin but nowhere near the quantities of the first layup. The removal of the release plies was significantly easier with the new orientation, with only a small amount requiring pliers to be removed. Immediately an improvement in the surface finish was noticeable with considerably less resin rich areas and a much smoother surface. As the release ply had been removed from the deepest section of the mould, it was apparent that the capping layer of glass had buckled slightly and was not conforming to the layers underneath correctly. This indicates that that area was not under enough pressure during the cure, possibly due to the pleat arrangement.

As with the first layup the small section of the mould separated as intended by winding in the bolts to push the two halves apart. The mould was then placed straight into the freezer. Upon removal from the freezer the part was again heated through the use of heat guns, however it did not release as easily this time. This problem was compounded by the carbon being opaque. The visual indication of the part releasing could not be seen and as such it was not apparent where the part was stuck. Fortunately sliding some thin plastic cut from a milk bottle, under the end section of the part managed to free it. Inspecting the inside of the part the carbon appeared not to deviate from the contours of the wheel proving that it could be formed around those surfaces. Again there were some resin rich areas and some voids, however the voids were of a different nature. They did not consist of an air bubble in a complicated section of geometry as with the first layup, but rather an entire area where the resin closely hugged the fibre weave but did not provide a smooth surface on the mould. This could possibly be caused by the carbon fibre in above drawing all of the resin that it could from the lower layer in an attempt to wet out. The final part will be manufactured from commercially available prepreg and as such should not suffer from these problems. The part was expected to weigh 410 grams and weighed 370 grams from upon removal from the mould (again showing signs of resin bleed) and 310 grams after the edges were roughly finished.

4. Summary of Layup Two

This layup proved that a relatively thick carbon tape could conform to the complex surface of the mould and as such can be used in an attempt to make the structure more efficient. The changes made to the orientation and size of the release plies created a much smoother surface that would require much less hand finishing than the previous layup. The potential use of a flexible silicone bag instead of the rigid plastic that is currently used for vacuum bagging should be looked into as this will allow the bag to conform to the moulding surface with more accuracy and provide a more evenly distributed pressure over the part.

Figure 14. The second layup glass and carbon rim after the edges have been trimmed

While the rim still released from the mould with the method developed for the first part and the use of a higher temperature cure in the auto clave will cause some expansion of the mould during cure, the application of a secondary release, for example, silicone release, in addition to the aluminium should improve the release of the part from the mould.

XII. Alternate solutions

The three major problems that are associated with this project are fibre control during layup and corrosion during long term use of the aluminium wheel centre due to the galvanic cell established with the CFRP.

A. Fibre control

Due to the double curvature of the mould the layup of woven cloth moves fibres away from their intended locations as the cloth attempts to form to the shape of the part. As the majority of the loads in a composite material are supported through the fibre material, the movement of these fibres has a significant impact on the properties of the final product. Additionally as the wheel rims will be manufactured by hand each wheel will have its own individual discrepancies. These differences have the potential to be as small as one or two kinked tows or as large as entire layers being offset or rotated. As such each wheel will have different mechanical properties and needs to be tested to ensure compliance with the aluminium wheel and the design requirements. The removal of these differences will reduce the time it takes to manufacture the wheels, greatly boost the quality control and therefore safety of the wheels and will reduce the cost associated with their production.

There are two main options that area available to improve the fibre control of the final part, they are the use of a unidirectional cloth or alternatively to filament wind/ automatically tape place the fibres into the correct location. Unidirectional cloth allows the cloth to be cut to the correct shape so that when it is placed on the mould it remains in the correct orientation without shearing to adapt to the mould surface. This requires more layers as tape placement or filament winding are based on the same principle as unidirectional cloth placement, however they are conducted on a much smaller scale and are usually computer controlled for accurate and repeatable placement.

Filament winding uses a single tow or filament to continually wind around the mandrel, this process is usually used for pressure vessels as it allows large portions or even the whole vessel to be wound from a single continuous tow, for a pressure vessel this is particularly advantageous as there is a constant stress due to the internal pressure that needs to be reacted at all points on the vessel. This reduces the requirement for the matrix to transfer the load from one fibre to any other via shear instead the fibre is in tension from the beginning to the end.

Tape placement, as the name suggests, places tape at controlled locations for controlled lengths on the mould. It doesn't necessarily use a continual length of fibre but can cut the fibre and start placement from a different location if required.

Both of these process allow for more accurate fibre placement and layup control than using a woven cloth over a double curve such as this wheel. However to achieve the required accuracy machinery that the university does not own is required. Tape placement can be conducted manually, though from some trials that the author conducted, a reasonable level of experience is required to maintain constant angles around the rim mould. There are some external companies that are able to tape place or filament wind over a custom mould. One such company is CST Composites, and Australian company with offices in Melbourne and Sydney.

CST Composites produces filament wound or tape placed products for sailing, industrial or research uses and offer filament winding or tape placing on custom mandrel which they will produce if requested. I have contacted CST Composites about the possibility of tape placing on my mandrel. While they were not directly against the idea they did not seem particularly interested in working with a small production run component. Additionally modifications to my mould would be required for it to be a suitable mandrel for their machines. This would be billed at a rate of $200 an hour which I believe would be an excessive cost considering the financial capability of the Academy Racing Team. If the marketing team were to approach the company and arrange some semblance of a sponsorship agreement the filament winding or tape placing of the rims would be a viable option.

B. Galvanic corrosion

The best way to reduce the galvanic corrosion issues would be through the use of materials that are in similar locations on the galvanic scale. In this case titanium is very close to carbon fibre and as such will not corrode because of the carbon fibre. Titanium also has high specific strength and high specific stiffness. However it is almost twice the density of Aluminium and as such requires very thin efficient structures to provide a structure that out performs the aluminium wheel centre.

The Academy Racing team has worked with Fomero, a rapid prototyping company, to make intake components for the car previously. Fomero has recently acquired the ability to make selectively laser melted (SLM) titanium components of up to an eight inch cube in size. As such a secondary wheel centre was designed that would take advantage of the unique manufacturing capabilities of SLM. This wheel centre was of monoque construction with wall thicknesses as low as 0.4mm to make a highly efficient component. The preliminary design showed that the centre was stiffer than the aluminium one intended to be run on the CFRP rims and only 3/4 of the weight. This design was discussed with Fomero who roughly quoted its production at $5000 per unit. As this cost was well outside of the budget of the Academy Racing team the design was not continued any further. However it is included here as an example of a possible future solution to galvanic corrosion in CFRC and metallic assemblies.

Figure 15. The proposed titanium wheel centre

XIII. Testing of the current rim

The development of baseline stiffness data earlier in this thesis treats the wheel as a single cylinder of nominal ten inch diameter. This allows an equivalent carbon part to be manufactured ignoring any increases in strength or stiffness due to geometry. In actual fact the wheel is not a cylinder, but rather a highly complicate shape including large changes in radius and double curvature. These geometrical features increase the stiffness of the wheel and its load carrying capacity before buckling takes effect. Physical testing is required to properly measure the stiffness of the rim while it is installed in a wheel assembly. The physical testing becomes a requirement due to the complicated interaction between the tyre and the wheel and the way that the load is imparted from one to the other.

The physical testing will take the form of two main loading conditions. A cornering and bump combined load, and an acceleration and bump combined load. In both cases the bump load is a +4.5g load and the additional load at 1.6g. As this test is to ascertain the stiffness and not a proof loading the absolute force applied to the wheel in each test condition will only be 1250N. This load correlates to the force that would normally be experienced by the wheel when the car is accelerating 0.3G with a 1.6G bump, when the car has a 70 kilogram driver. As the car's weight distribution deviates less than 1% from 50/50 this analogy is valid for all four wheels.

The testing jig consisted of a plinth with a 20^{o} angled plate (from the horizontal) and a top arm that held the wheel at a 20^{o} angle (from the vertical) for the side load testing or with the axis of the wheel 85 mm offset from the loading axis for the longitudinal acceleration testing. The 20^{o} inclination angle was developed from the arctan of 1.6/4.5 (the ratio of the "g" forces) and manufacturing tolerances. The bottom component of the test rig was able to be used for both tests requiring only a rotation of 90^{o} when the assembly was changed.


Figure 16. The lateral load testing assembly.

The testing jig was constructed from 75*50 RHS with a 3mm wall. This ensured that it would have adequate stiffness for the testing while still being light enough to move with only one person. The orientation of the material was such that the second moment of area was maximised for any sections that were in bending again to further increase the stiffness of the assembly.

The deflection of the wheel was primarily measured using two dial gauges on the rim. A line was drawn on the rim that ran parallel to the axis of rotation and both dial gauges were acting on this line. One dial gauge was located approximately 3mm from the vertical step to the wheel centre and the other was located at the very edge of the rim past the bead lip. The dial gauges were magnetically mounted to the upper section of the jig so that they would have as small as possible movement relative to the wheel rim and the use of the two dial gauges allows for a differential measurement to be established so that the displacement of the lip of the rim relative to the wheel centre can be measured instead of measuring assembly deflection. As the torsional deflection of the wheel cannot practicably be measured with the use of dial gauges, a strain gauge rosette was installed on the same line that the dial gauges were measuring.

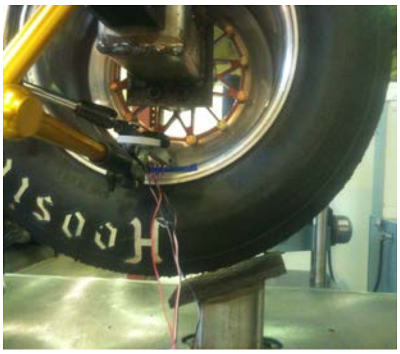
Figure 17. The longitudinal load testing assembly. *The offset between the wheel centre and the contact patch is apparant*

These measurements will allow a comparison for the testing of the carbon fibre rim. Due to the isotropic nature of composite materials the testing that was conducted here would not be adequate on the final product. The equipment and the method can be used, but the quantity of measurements needs to be significantly increased. The first rim requires testing with strain gauges on the bead radius lip of both beads to ensure consistency and another strain gauge to be located on the long flat between wheel centre the centre and the bead. These strain gauge locations are required to be repeated every 90^{o} this will allow the installation orientation of the wheel to be changed (the bolt pattern only allows for a minimum of a 90^{o} rotation) and subsequently checked to ensure that there are no significant variations in the structural properties of the wheel due to the layup in what should be an axially symmetric item.

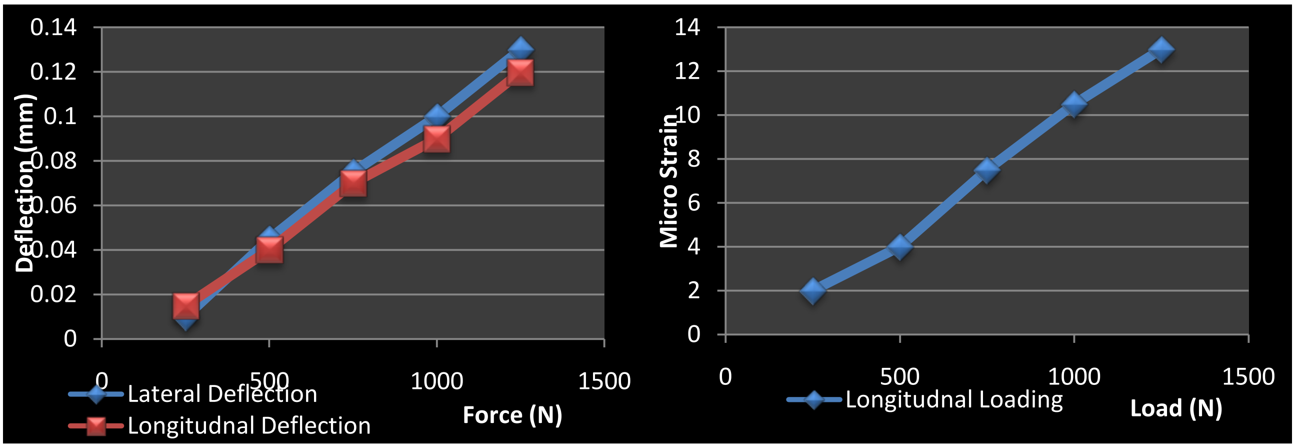

Figure 18. The deflection and shear strain from the rim testing.

While the first wheel manufactured is being tested it needs to be tested to the proof load to ensure that the bolted connections are correct. During this testing strain gauges can also be used to check that the wheel is safely within the failure strain. When the wheel is off the testing machine each of the contact patches between the rim and the wheel centre are to be visually inspected for any signs of deformation. They should again be inspected with the thermal camera and a heat source to look for any delaminations that may be buried in the laminate and not visible to the naked eye.

XIV. Conclusions

The use of a CFRP wheel rim has the potential to improve the performance of the Academy Racing FSAE vehicle by lowering the unsprung mass and the rotational inertia of the wheel assembly. Additionally a wheel rim that is manufactured in house can have sufficient quality control applied to it such that it does not exhibit the problems of the current COTS wheels that the team uses. This will improve the confidence level at which the wheel can be operated at safely, and also allow further testing options as the useable operating pressure range of the wheel is increased.

Tailoring the layup to use unidirectional material in addition to the use of a woven cloth reduces the material required and the cost per part, in addition to this the tailoring of the rim to meet the required load cases increases the efficiency of the component and further reduces the weight of the final product. In light of this the most economical way to produce the rim in large quantities would be through the use of unidirectional tape placement, if these facilities were able to be used at cost price. However as the labour and profit costs have to be taken into account the price for this layup becomes prohibitive for a small manufacturing run such as these components. For the Academy Racing team the most economical method of manufacture is through hand layup utilising the universities composite facilities.

The intended mould that the rims are to be manufactured on successfully makes a part that has a high finish quality and releases without excessive effort. Additionally the CFRP material is able to conform to the complicated surface without lifting or fibre breakage implying that parts manufactured should be of high enough quality to be used in a primary structure application. In saying this the preparation of materials, in shape and orientation is important in ensuring that a high quality part that is safe for operation is produced.

The complicated nature of composite design means that the solutions provided in this thesis still require further testing and validation to prove that the composite wheel rim is safe for use on the Academy Racing FSAE Vehicle.

XV. Recommendations

In order to validate the designs conducted in this thesis a wheel centre of M. Olsen's design should be manufactured and mated to a composite rim and then tested to prove its adequacy.

XVI. Acknowledgements

Firstly and most importantly I would like to acknowledge my thesis supervisor Mr Alan Fien. After knowing him as a lecturer for over 5 years he still amazes me with the depth of his knowledge in any subject that I can think of. He provided a great deal of assistance to me through this project and constantly forced me to strive for the better solution. In my opinion you don't know what you don't know until you talk to Alan.

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Lastly I would like to thank my parents, Ken and Jenni Chapman for their support and for encouraging me to be inquisitive for as long as I can remember, a trait that I believe led me to engineering.

XVII. Appendices

A. Initial Project Timeline
B. Revised Project Timeline
C. Wheel Centre Drill Jig Drawing

XVIII. References

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