Design, Analysis and Manufacturing of Carbon Fiber Rims for a Formula Student Vehicle

Dr. N. P. Sherje[#1], Ms. Manisha Gawai[*2], Mr. Atharva Padhye[#3], Mr. Atharva Deokule[#4] , Mr. Rahul Agrawal[#5]

[#]*Mechanical Department, Smt. KashibaiNavale College of Engineering, Pune*

***Abstract*— In this project we dealt with complete design of rims using CAD models, analysis of the rims to check their life via Ansys Composite Pre-post and simulation software and in house manufacturing of the final product.**

***Keywords*— Carbon Fibre, Epoxy Resin, Vehicle Dynamics, Wheel loads, Wheel Assembly**

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 department's 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 characterized 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 characterized by the equation: $\omega\omega 0= \surd\, mm1$ $kk2$ Where $\omega\omega 0$is the undamped natural frequency, $kk2$ the wheel rate (spring constant taking into account any motion ratios) and $mm1$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):

$$mm1xx\ddot{1}=-kk1xx1+kk2(xx2-xx1)mm2x\ddot{x}2=-kk2(xx2-xx1)$$

Where $xx\ddot{1}$ and $x\ddot{x}2$ are the accelerations of the unsprung and sprung mass respectively $mm2$ and $mm1$are the masses, $kk1$ and $kk2$ are the spring rate of the tyre and the wheel rate respectively and $xx1$ and $xx2$ 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:

$$x\ddot{x}1=-xx1kk1\ mm1-mm2x\ddot{x}2\ mm1\ x\ddot{x}\,2=-xx1kk1\ mm2-mm1x\ddot{x}1\ mm2$$

Decreasing $mm1$ will increase $x\ddot{x}1$ which will allow the suspension to keep in constant contact with the road. An increase in $mm2$ will lower $x\ddot{x}2$ keeping the chassis position relatively constant. It is shown then that as $mm2\ mm1$ 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 newton's 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. 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 allhave 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).

C. *Fabric Selection*

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). 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).

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.

VI. 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.

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.

VII. 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 IBeam. 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.

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.

References

1. ACME Racing. (2010). ACME Racing Design Loads. Canberra.
2. Barbero, E. J. (2008). Finite Element Analysis of Composite Materials. Boca Raton: CRC Press.
3. Barbero, E. J. (2011). Introduction to Composite Materials Design. Boca Raton: CRC Press.
4. Bosch. (2007). Automotive Handbook 7th Edition. Warrendale: Society of Automotive Engineers.
5. Christensen, R. M. (1979). Mechanics of Composite Materials. Mineola: Dover Publications.
6. Dassault Systems. (2009). CATIA V5R18 Online Documentation. France.
7. Dorworth, L., Gardiner, G., &Mellema, G. (2009). Essentials of Advanced Composite Fabrication and Repair. Newcastle: Aviation Supplies and Academics.
8. Harwood Performance Source. (2010). Blackstone Tek BST Carbon Rims. Retrieved August 15, 2010, from Harwood Performance Source: http://www.bikehps.com/bst/
9. Hilado, C. J. (1974). Carbon Resinforced Epoxy Systems. Westport: Technomic Publishing.
10. Huntsman. (2004, August). MSDS - 420 A/B. No. A 161 g GB. Huntsman.
11. Inaman, D. J. (2001). Engineering Vibration. Upper Saddle River: Pearson Education.
12. Lubin, G., & Peters, S. T. (1998). Handbook of Composites. London: Chapman & Hall.
13. 28 Undergraduate Thesis Report 2011, SEIT, UNSW@ADFA