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Design and Analysis of a Composite Wheel Rim

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Abstract : *Vehicle mass can be categorized as sprung-mass and unsprung-mass. Lower values of unsprung mass leads to faster response time. There will be a steady vertical load acting through the tyres and therefore a consistent level of friction acts between the car and road. Acceleration, braking and cornering performance of the vehicle is better. This paper aims to develop a composite wheel rim to be used with a lightweight aluminum center to reduce the unsprung mass of the vehicle and thus decrease the suspension response time for greater control of the vehicle. This will work towards bringing the sprung to unsprung mass ratio closer to the original value, and therefore allow for further reduction of the unsprung mass as well as sprung mass.*

Keywords: *Sprung-mass, Unsprung-mass, Response*

1. INTRODUCTION

10 inch or 13 inch rims are supplied commercially by wide range of suppliers. The average weight of the wheels from theses suppliers vary from 2 to 3.5 kilograms. This includes a 6061 KOSMO Magnesium Series aluminum rim from Keizer racing. Carbon fiber solutions are also available, such as the 1 kilogram carbon fiber shell from CS-wheels. The carbon fiber solution excludes the wheel center, which if purchased would bring the whole wheel to about 1.6 kilograms. This option only saves half kilogram from the aluminum solution, and at Rs.30000 per wheel, this solution is prohibitively expensive.

There are a limited number of composite wheel products on the market for road cars, race cars and automobiles in varying sizes. However due to the emerging nature of this technology manufacturers are not willing to provide information on their construction techniques.

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.

2. 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 force must be maintained. 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. 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. This system is characterized by the equation:

$$\text{undamped natural frequency } (\omega_0)=\sqrt{\frac{\text{wheel rate } (k_2)}{\text{unsprung mass } (m_1)}} \quad \textbf{(1)}$$

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 sameresults can be achieved by increasing the spring stiffness this also decreases the suspension travel and means thatthe suspension relies on an increasingly smooth track. As such the ideal unsprung weight is zero, so thesuspension can be relatively softly sprung and the wheel can follow all undulations in the road without losingcontact. Using a two degree of freedom system taking tyre vertical stiffness into account the equations of motionbecome:

$$\begin{aligned}&\text{unsprung mass } (m_1) \text{ X acceleration of unsprung mass}(\ddot{x})\\&= -[\text{spring rate}(k_1)\ X \text{ position of suspension(x)}]\\&+ [\text{Wheel rate } (k_2) \text{X } \{\text{position of chassis(y)}\\&- \text{position of suspension(x)}\}] \quad (\mathbf{2})\end{aligned}$$

$$\begin{aligned}&\text{sprung mass } (m_2) \text{ X acceleration of sprung mass}(\ddot{y}) =\\&-[\text{Wheel rate (k2)X } \{\text{position of chassis(y)} -\\&\text{position of suspension(x)}\}] \quad \textbf{(3)}\end{aligned}$$

Rearranging this equation to view one acceleration predominantly as a function of the other and the masses gives:

$$\ddot{x} = -\frac{x\mathrm{k}_1}{\mathrm{m}_1} - \frac{\mathrm{m}_2\ddot{\mathrm{y}}}{\mathrm{m}_1} \quad \textbf{(4)}$$

$$\ddot{y} = -\frac{\ddot{x}\mathrm{m}_1}{\mathrm{m}_2} - \frac{\mathrm{k}_1 x}{\mathrm{m}_2} \quad \textbf{(5)}$$

Decreasing m_1 will increase $\ddot{x}$which will allow the suspension to keep in constant contact with the road. An increase in m_2 will lower $\ddot{y}$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 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.

3. METHODOLOGY

Material Selection

Composite materials are light weight with high specific stiffness and strength compared to traditional isotropic materials such as metals. 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 than its constituents. 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. So the fibres can be oriented in various directions such that they meet the specific requirements of the load paths which 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 product.

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 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.

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.

Fabric Selection

Fig. 1: Friction Ellipse(MATLAB)

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 and the comparative strength of the fabric along the principle axes, the specific fabric orientation is defined by the intended use of the fabric.
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.

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. When a core is used it is referred to as a sandwich panel construction.

Tyre Data

Tyre is the fundamental component to determine vehicle dynamics and handling. Improvement in vehicle performance (keeping in mind the lateral and longitudinal dynamics) can be done with the help of tyre properties. Tyre simulation is important to understand the longitudinal and lateral dynamics of a tire. So data from an actual tyre stimulation was used to understand tire behavior which will be used for obtaining tyre contact patch forces.

Raw Data

The raw data is a large array of data gathered from testing of a tire on the test machine at Calspan. These data have 8 inputs given by the test machine and 14 outputs gathered from it, all arranged in form of a matrix. Raw data is all the output of the values been tested during the particular run of the tire. It is the direct value of forces, moments, temperatures and radiuses without alterations, fitting or hysteresis removal. This data needs to be sorted out, fittedand plotted so that it can be further used for calculating forces.

Importing and De-multiplexing

Tyre data has to be imported into MATLAB workspace in form of a matrix. The cornering runs for Hoosier 20.5 x 7.0 - 13 R25B with 7 inch rim width were imported into the workspace. Then the two cornering data are combined into one so that it is easy to work with them. Then these arrays have to be given variable names according to the convention for which another matrix containing the names of these arrays is used.

Sorting data according to required inputs

There were a lot of inputs during tire testing. All the values of pressure, normal load and camber are not required at the same time. So these data are sorted in different ranges to make slots of data so that each of these can be fitted individually.

Removing warm up data

Tire warm up is done before starting any round of tire testing. This is manually found out and removed. To find out warm up data timings in case of cornering data a graph of Slip Angle versus Elapsed time is plotted. In case of combined diving test, Slip Ratio versus Elapsed time is plotted. The pressure values are equated to 0 so they automatically assume value of 'false'. So when a Boolean array is created, these values don't come up while fitting.

Scaling

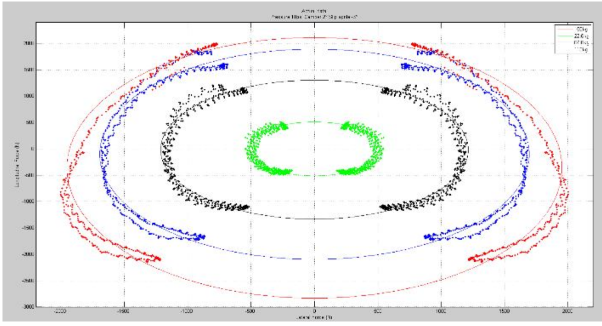
The belt on the test machine at Calspan is very clean and very smooth, so the peak friction values in the test data can be higher than what is seen on a typical racing surface (or parking lot). In past Rounds the "real world" peak lateral and longitudinal forces reported by FSAE teams are roughly 2/3 of those seen at Calspan.

Such disagreement is always an issue with laboratory tire testing. How well or poorly the magnitudes agree are a strong function of tire construction and compound.

The chosen value for scaling is 0.65 after reading a few papers and gathering information from forums. All the lateral, longitudinal and normalized forces are multiplied by this scaling factor.

Data fitting and plotting

The final step of tire data modeling is data fitting and plotting. The sorted raw data is fitted into a polynomial of certain degree. This is done by using the command 'polyfit'. But in



case of ellipse e.g.: g-g diagram a different function EllipseDirectFit is used.

Force Calculation Spreadsheet

In order to calculate the load in each case an excel spreadsheet calculator was developed based on the following load transfer equations.

$$Longitudinal\ Load\ Transfer = \frac{W_{cg} * CG\ Height * g_i}{W_b} \quad \textbf{(6)}$$

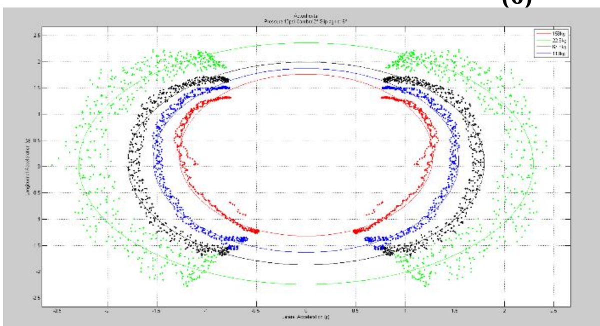


Fig. 2: g-g Diagram (MATLAB)

$$Front\ Lateral\ Load\ Transfer = \frac{W_f * Front\ CG\ Height * g_f}{F_t} \quad \textbf{(7)}$$

Table 1: Maximum possible G's experience in the lateral and longitudinal direction for each dynamic loading case

Loading Case	Maximum Possible Load (G)	
	Lateral Load	Longitudinal Load
Cornering	1.69	0
Acceleration	0	1.5
Cornering and Acceleration	1.05	1.05
Braking	0	1.49
Braking and	1.05	1.05

Cornering		

$$Rear\ Lateral\ Load\ Transfer = \frac{W_r * Rear\ CG\ Height * g_r}{R_t} \quad \textbf{(8)}$$

Establishing Load Case Scenarios

The rim is normally loaded through the tire. The tire itself is loaded specifically in an area called the tire contact patch, where the tire makes contact with the ground. The tire contact patch size varies for each tire, but from pictures of the vehicle during operation, the tire contact patch is approximately 3 inches by the width of the tire.

To simplify the loading for analysis purposes, the loading of the tire was considered to be a remote point force at the center of the tire contact patch. This remote force was applied to the rim via the tire bead seat. The hub face of the rim, which is the section that is compressed against the spindle, was considered fixed.

Table 2: Forces from Force Calculation Spreadsheet (in Newtons)

Force Direction	Cornering		Acceleration	
Longitudinal	0	0	554	554
	0	0	1954	1954
Lateral	900	1350	0	0
	0	2660	0	0
Normal	434	806	195	195
	7.6	1762	1309	1309

Table 3: Forces from Force Calculation Spreadsheet (in Newtons)

Force Direction	Acceleration and Cornering		Braking		Braking and Cornering	
Longitudinal	0	648	-1776	-1776	-1445	-1783
	841	2500	-800	-800	0	-1856
Lateral	0	714	0	0	1557	2044
	839	2700	0	0	-1856	2282
Normal	9.3	381	1044	1044	858	1230
	432	2186	460	460	416	1337

Various Load Case Scenarios such as Cornering, Acceleration, Braking, Braking and cornering, and Acceleration and cornering were examined. In order to avoid wheel failure, four critical load cases were developed to represent the most extreme conditions the wheel rim would experience during operational use.

The angle of deflection was calculated by taking the tangent of the deflection over the radius of the rim. This method makes the assumption that wheel deforms with a constant slope along the radius, acting as a rigid plate. While this does not capture the true deformation of the wheel, it simplifies the quantization of the wheel deformation for easy comparison.

$$\tan \emptyset = \frac{Deflection}{Radius\ of\ Rim} \quad \textbf{(9)}$$

Fig. 3: Rim Profile Parameters

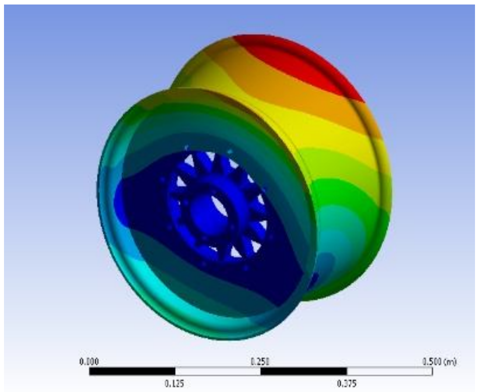


Fig. 4: Deformation Due To Acceleration

Rim Profile Design using CATIA

Table 4: Design Specification Sheet

DESIGN PARAMETER	CONTRAINT
Width of Rim	L_1+L_2=177.8mm

Angle	$5^o < \theta_1 < 10^o$	$5^o < \theta_2 < 10^o$
Offset	L_1/L_2 varies depending on the offset required	
Tyre Beading	Values of R1,R2,R3,R4 obtained from rim profiles of standard rims as they depend on tyre beading	

Design Concepts

Following five design concepts were developed:

1. Aluminium rim with Aluminium wheel center (3-piece rim)
2. CFRP rim with Aluminium wheel center (3-piece rim)
3. CFRP single piece rim with Aluminium wheel center
4. Aluminium outer shell and CFRP inner shell Aluminium wheel center
5. Aluminium Inner shell and CFRP outer shell Aluminium wheel center

Each of these five concepts are analysed using ANSYS. Once the loading conditions were finalized, five concept designs were developed. In order to compare theses designs without expending a large amount of time refining each design to every loading condition, a specific stiffness metric was developed. This metric was used to evaluate the efficiency of each design compared to the weight of it. It was calculated per the following equation:

$$Specific\ Stiffness = \frac{\frac{Applied\ Moment}{Deflection}}{Wheel\ Weight} \quad (10)$$

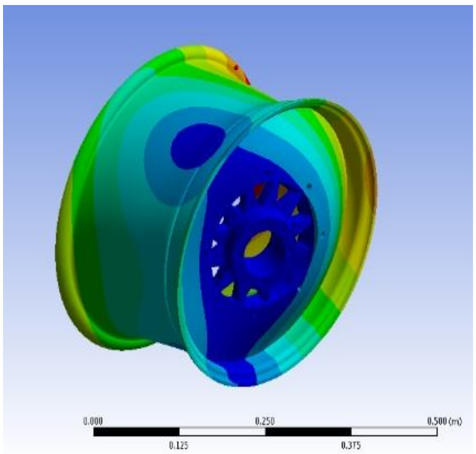
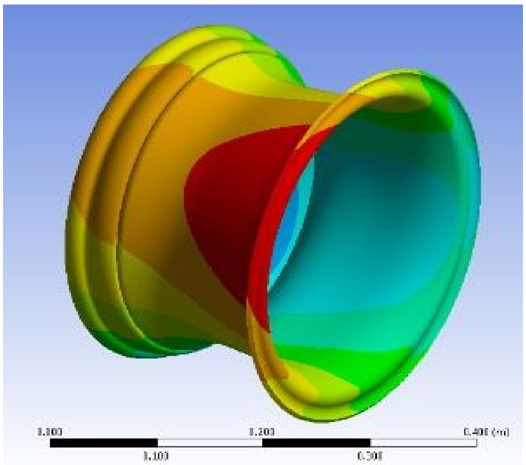


Fig. 5: Deformation Due To Cornering

Wheel Center Design using CATIA

Key design considerations for wheel center are:

i. Minimize mass, especially at radial extremities to reduce MMOI.
ii. Stiffness
iii. Constant bending moment along any radial line from conta ct patch to axis of rotation to produce an even stress distribution and minimize unnecessary mass.
iv. Manufacturability and cost



Analysis of Aluminium Rim Using ANSYS Static Structural

Fig. 6: Deformation Due To Cornering and Acceleration

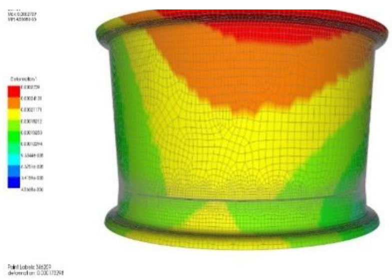


Fig. 7: Deformation in a Carbon Fibre Rim

Analysis of Composite Design Concepts using ANSYS Composite PrepPost

Meshing

The mesh quality was improved for accurate solution, meshing in certain areas of the geometry like the tyre bead seat was refined where the gradients of the field whose solution is sought is high. In most cases a tetrahedral volume mesh was generated using Path Conforming Method. The wheel centre has hexahedral meshing but the rim has tetrahedral meshing because the body selected for hex dominant meshing had a small normalized volume to surface area ratio. This may result in a low percentage of hexs or poorly shaped elements. So the method control was changed to Tetrahedrons.

Design Optimization and Selection

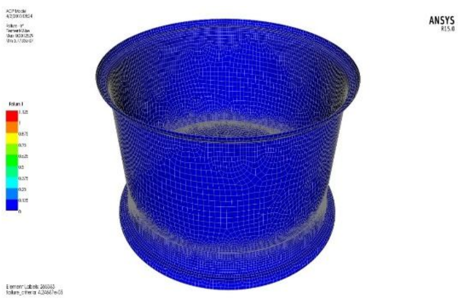


Fig. 8: Fatigue Analysis of Carbon Fibre Rim

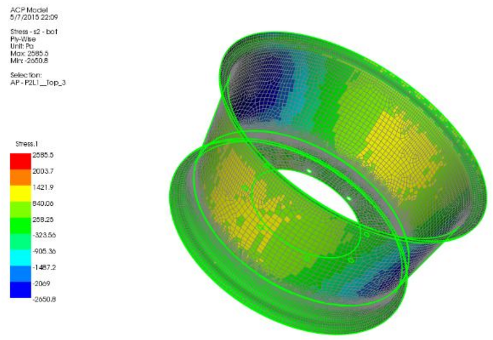


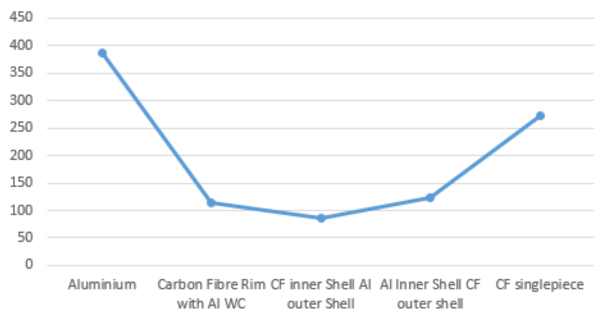
Fig. 9: Stress Distribution in Carbon Fibre Rim

RESULTS

During acceleration the maximum deformation was 0.1mm in case of aluminium rim with maximum lateral deflection of 0.034. During cornering the maximum deformation was 0.6mm with maximum lateral deflection of 0.208. During Cornering and Acceleration the maximum deformation was 0.653mm and the maximum lateral deflection was 0.21.

During the Composite Analysis of the Carbon Fibre Rim the stress values varied from 2585.5 Pa in tension to -2650.8 Pa in compression. High stress distribution was observed on the third ply from top in the stack-up as shown in Fig.9. There were patches where the stress distribution varied from 840.06 Pa to 1421.9 Pa but mostly throughout all the plies the stress values varied from -323.56 Pa in compression to 840.06 Pa in tension. The maximum deformation was 0.2709mm.

Fig. 10: Specific Stiffness of all Design Concepts



Clearly among the Carbon Fibre Design Concepts the single piece CF rim has highest Specific Stiffness but a 3-Piece CF rim was chosen as manufacturability issues are less. The final design selection has 8 plies with 15mm thick hard-foam core.

CONCLUSION

The use of a CFRP wheel rim has the potential to improve the performance of FSAE vehicles by lowering the unsprung mass and the rotational inertia of the wheel assembly.

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

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