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Design Optimization of Electric Vehicle Wheel using Composite Materials

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Abstract

In an electric vehicle, the wheels are one of the heaviest components of the vehicle. This paper aims to reduce the mass of the existing wheels for reduction in energy consumption as well as increasing the precision in steering. In this paper, an electric sedan is taken as the reference for studying the wheel and the boundary conditions are decided according to its specifications. Reduction in mass is achieved by designing a composite wheel for the boundary conditions. A reduction of 58% is achieved on the total mass of wheel.

Keywords: Energy efficiency, Composite materials, wheel

1. Introduction

The need for energy efficiency in electric vehicles is of utmost importance for increasing the travelling range of the vehicle. For maximum range with the available power, reduction in mass of the vehicle is required. Vehicle mass can be categorized as sprung- mass and unsprung-mass. The wheels are considered a part of the unsprung masses, which are parts that are not supported by the car suspension. The unsprung masses have an impact on the driving characteristics, as by reducing them, the suspension will more easily keep contact between the tyres and the road surface. As the wheels are assumed to have the highest impact, it is important to focus on them. Composite wheels bring down the mass of the usual aluminium wheels. Carbon fiber composite wheels are 1.7 times lighter than aluminium and have higher strength, stiffness and fatigue resistance and are thus chosen here as the material for thewheel.

2. Literature review

In [1 – 4], design, material optimization and dynamic analysis on automobile wheel rim is demonstrated that there is large scope for reducing the mass of aluminium wheel by changing or replacing the materials with composites to increase the bearing of stresses and to decrease its mass and volume. From the finite element calculations, it is found that the mass of the wheel rim can be reduced to 50% from the existing alloy wheels by using composite materials. The analysis also shows that after the optimization the stresses generated from the wheel rim will be below the yield stress.

[5 -7] describe advanced methods that can be used to carry out analysis of a car wheel rim for weight reduction. At other places, the wheel rim is modeled and analyzed to see the variations of deformation and stresses of the rim for different material such as Aluminium Alloy, PEEK, PEEK with 30% Glass fiber, PEEK–90 HMF 20, PEEK–90 HMF 40. The analysis is carried using ANSYS for different compositions of the PEEK materials.

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3. Problem formulation

The initial aluminium alloy five spoke wheel was designed according to the dimensions of wheel of an electric sedan. The wheel is of dimensions 245/45R19 (refer Figure 1), where total weight is 18.875 kg, hoop is 7.3 kg, spokes are 9.11 kg and hub is 2.55kg.

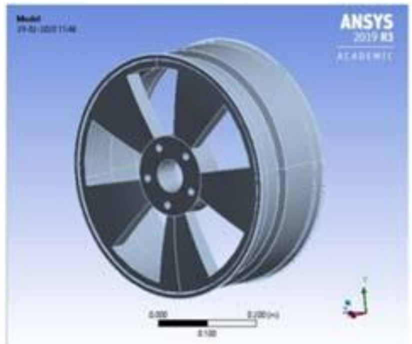

Figure 1: Wheel Model

For the stress and deformation analysis of the wheel, the following boundary
conditions have been considered:

a. The wheel is subjected to a vertical force (radial load) due to the weight of the vehicle. The reaction of each wheel from the ground (which is the radial load), can be calculated asfollows:

Solving the equilibrium equations for the model (refer Figure 2), we get the wheel reactions as [1]:

$$R_F = \frac{Mg(L-a)}{L+\mu h} \tag{1}$$

$$R_R = \frac{Mg(a+\mu h)}{(L+\mu h)} \tag{2}$$

where,

M: mass of the car, g: gravitational acceleration=9.81m/s^2

RR: reaction force on rear wheel, RF: reaction force on front wheel

a: distance between centre of gravity of car and rear wheel, L: wheelbase of car

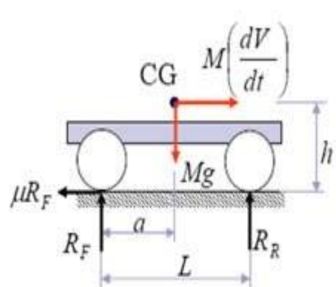

Figure 2: Reactions on Wheel

Considering the weight distribution and specifications in a typical electric sedan car, we have the following:

a =1.56m, h=0.46m, M =2500kg, L=2.96m

Thus, we get, for each wheel,
RR= 7293N, RF = 4970N. Thus, the maximum reaction acting on a wheel is 7293N.

a. The wheel is subjected to the opposing torque produced by the frictional force acting on the wheel. Considering an electric sedan, the specifications taken are as follows:

Torque produced by motor = 440Nm
Reduction Ratio=9.73
Thus, the torque acting on the wheel is 440 × 9.73 = 4281.2 Nm

b. The wheel is subjected to tire pressure. For the electric sedan, the tire pressure is taken as 276KPa.

4. Method of analysis

CFRPs (Carbon Fiber Reinforced Polymers) are light, have high strength, stiffness and fatigue resistance and were chosen as the material for the wheel. From the options available of CFRP, it was decided to use pre-impregnated (prepreg) carbon fiber material. A prepreg material is a fiber reinforced resin matrix that comes ready to use in manufacturing, unlike more traditional wet-layup materials that require the resin matrix to be mixed and applied to the dry fiber fabric during manufacturing. This allows for a cleaner, more efficient layup process [2]. The use of epoxy as a matrix has been chosen as it is easy to work with, reasonably inexpensive and is the most common form of carbon reinforced pre-impregnated fabric (prepreg), making it easier to obtain than some of the other resins available. Furthermore, epoxy resin systems emit limited quantities of styrene 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 [3]. The type of epoxy resin chosen is Diglycidyl ether of Bisphenol A (DGEBA) resins with polyamine hardeners. They are one of the most common epoxies used for composites. They are quite flexible in terms of properties (at the resin manufacturer level), provide good overall mechanical properties, cure at relatively low temperatures and are not the mostexpensive.

When modeling composite laminates, it is critical that ply orientations are carefully considered and controlled. In this case, the composite shells are broken up into two main entities; the hoop and the spokes. In the hoop, the 0° plies are oriented along the circumference, and 90^0 are oriented axially. On the other hand, the spokes have the 0°plies oriented radially along each spoke since these members are predominantly under tension and compression in radial direction.Epoxy Carbon UD (395GPa) Prepreg is chosen as the material for the hoop.

The acceleration and braking forces cause torsion in the wheel, and these loads are best transferred through the use of a ±45° fabric so that they are balanced in both acceleration and braking [3]. Hence, layers of ±45° fabric is needed. It is also a good idea to place a±45° woven layer on the outside surfaces of a part to increase wear and damage tolerance, as well as reduce possibility offraying.

The longitudinal load acting on the wheel rim, considered as a hollow cylinder, creates torsion, and the angle of twist is given by

$$\varphi = \frac{\tau l}{JG} \tag{3}$$

where,
φ: angle of twist, l: nominal length of wheel rim,
J: polar moment of inertia of wheel rim,
G: Shear Modulus of material
Now, the aluminum alloy rim and composite rim are considered to have the same angle of twist

for the same torque [3].Therefore,

$$\frac{\tau l}{J_{Al}G_{Al}} = \frac{\tau l}{J_c G_c} \tag{4}$$

$$J_{Al} = \frac{\pi(d_1^4 - d_2^4)}{32} = \frac{\pi(0.4826^4 - 0.4756^4)}{32} = 3.023 \times 10^{-4} \tag{5}$$

GAl = 26 GPa, Gc= 44 GPA

Thus, with l = 0.2032m, Jc = 1.7×10^{-4}. Therefore, d2 = 0.478m and d = d1 – d2 = 3.8mm, i.e. t(thickness of composite wheel hoop) = 1.9mm, thus approximately 2 mm. Thus, considering 0.2mm thickness lamina, we need 10 45^0 woven laminae.

Now, the vertical load acting on the rim creates a bending moment. The wheel rim can be considered as a hollow cylinder fixed at one end (wheel hub end), and the vertical load acts at a distance of l (horizontal distance between wheel hub and bead area)[3]. Thus,

$$\sigma = \frac{My}{I} \tag{6}$$

This can be rearranged as

$$\frac{Fyl}{\varepsilon} = EI \tag{7}$$

Here, F(force), y, l(length), ϵ(strain) are considered same for the aluminum alloy rim and composite rim. Thus, we get EAlIAl = EcIc.

$$I = \frac{\pi(d_1^4 - d_2^4)}{64} \tag{8}$$

$I_{Al}=1.51\times10^{-4}mm^4$,$EAl=7.1\times10^4MPa$,$Ec=2.09\times10^5MPa$,$Ic =1.134\times10^{-3}mm^4$.

Thus, d2 = 0.4802m. And thickness(t) = 1.17mm, i.e., approximately 1.2 mm. Thus, we need 6 90^0 laminae.

The tire pressure acts on the hoop, and stress developed is given by

$$\sigma = \frac{Pr}{t} \tag{9}$$

where σ = 893 MPa P(pressure) = 276KPa, r(radius) = 0.2413m and thus t(thickness) = 0.08mm. Thus, 1 layer of 0^0 is required for the hoop. Also, due to radial loads acting on the wheel, the bead area is subjected to circumferential stress, and hence a safety factor of 3 is used, and the number of layers of 0^0 is increased to 3.

The laminas for the hoop are stacked up as follows: 5±45° woven lamina, 3 90^0 lamina, 3 0^0 lamina, 3 90^0 lamina and 5±45° woven lamina. Midplane symmetry is maintained to prevent warping during manufacturing [4].

Now, the spokes are substituted with the composite material. Epoxy Carbon Woven (395GPa) Prepreg is chosen as the material for the spokes as stresses are present in x and y directions at different orientations of spoke with respect to part of tire in contact with ground. Consider the case when only one spoke is taking all the loads as it is perpendicular to the ground. Consider for each spoke there is a local coordinate system for the direction of fibers. The 0^0 direction of fibers is oriented in the radial direction of each spoke. The 90^0 fibers are in the axial direction. The loading conditions are (refer Figure 3): bending due to longitudinal force because of torque acting on wheel and vertical load. The tire pressure and lateral force have very less impact on stresses compared to these loading conditions and hence they are ignored for simpler analysis.

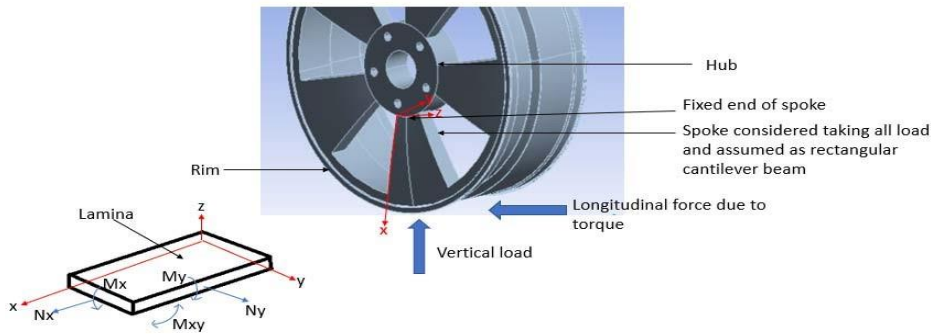

Figure 3: Loading conditions

Consider 30mm as the thickness of the spokes, reduced from 40mm of original design, due to better strength properties of CFRP. Consider the spoke as a rectangular cantilever beam, with the supporting end near the wheel center, and the free end near the hoop. Due to the torque acting on the wheel, and in the worst case when the wheel is stuck, maximum bending moment is acting at the section of the spoke near the center of the wheel. A force of 4281.2 /0.2413(radius of wheel) = 17742N acts at the end of this rectangular beam (near the hoop). The maximum bending moment acting on the spokes is near the center of the wheel, and is given by 17742*0.16(length of spoke) = 2838.72 Nm. The thickness of the spoke is 30 mm. Let M be bending moment per unit length. Thus, Mx = 2838720/30 = 94624N.

The vertical load is compressive in nature and equal to -7293 N. Let N be force per unit length. Hence, Nx = -7293/30 = -243.1 N/mm.

For Epoxy Carbon Woven (395GPa) Prepreg, E1 = 91.82 GPa, E2 = 91.82 GPa, v12 = 0.05, v21 = 0.05. Thus, in the Q matrix, Q11 = E1/(1- v21* v12) = 92050,Q12 = Q21 = v21*E2/ (1- v21* v12) = 4610, Q22 = E2 /(1- v21* v12) =92050.

$$Q = \begin{bmatrix} 92050 & 4610 & 0 \\ 4610 & 92050 & 0 \\ 0 & 0 & 3600 \end{bmatrix} \tag{10}$$

The force and moment resultants are related to midplane strains and curvature as follows:

$$\begin{bmatrix} N \\ M \end{bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{bmatrix} \epsilon^0 \\ k \end{bmatrix} \tag{11}$$

Now, as all laminas are of the same material and orientation, matrices A, B and D are:

$A = Qt$, $B = 0$, $D = Q[(t/2)^3 - (-t/2)^3]/3 = Qt^3/12$ where t is thickness in z direction = 50mm minimum at cross section near wheel center.

Thus, we get, $[N] = t[Q][\epsilon^0]$

$$\begin{bmatrix} N_x \\ N_y \\ N_s \end{bmatrix} = \begin{bmatrix} -243.1 \\ 0 \\ 0 \end{bmatrix} = 50 \begin{bmatrix} 92050 & 4610 & 0 \\ 4610 & 92050 & 0 \\ 0 & 0 & 3600 \end{bmatrix} \begin{bmatrix} \epsilon_1^0 \\ \epsilon_2^0 \\ \epsilon_s^0 \end{bmatrix} \tag{12}$$

Solvingthesimultaneousequations,weget,$\epsilon 1^0 = -5.29*10^{-5}$,$\epsilon 2^0 = 7.95*10^{-5}$,$\epsilon 6^0 = 0$

And, $[M] = (t^3/12)[Q][k]$

$$\begin{bmatrix} M_x \\ M_y \\ M_s \end{bmatrix} = \begin{bmatrix} 94624 \\ 0 \\ 0 \end{bmatrix} = \left(\frac{50^3}{12}\right) \begin{bmatrix} 92050 & 4610 & 0 \\ 4610 & 92050 & 0 \\ 0 & 0 & 3600 \end{bmatrix} \begin{bmatrix} k_1 \\ k_2 \\ k_s \end{bmatrix} \tag{13}$$

Solving the simultaneous equations, we get,

$$\begin{bmatrix} k_1 \\ k_2 \\ k_s \end{bmatrix} = \begin{bmatrix} 9.89 \times 10^{-5} \\ -4.95 \times 10^{-6} \\ 0 \end{bmatrix} \tag{14}$$

The maximum strain is at the furthermost layer from the midplane, and is given by

$$[\epsilon]=[\epsilon^0]\pm z[k] \tag{15}$$

$$\text{Thus, } [\epsilon] = \begin{bmatrix} -2.525 \times 10^{-3} \\ 2.03 \times 10^{-4} \\ 0 \end{bmatrix} \text{ and } [\epsilon] = \begin{bmatrix} 2.42 \times 10^{-3} \\ -4.4 \times 10^{-5} \\ 0 \end{bmatrix}. \tag{16}$$

The stresses in the layers under maximum stress are thus $[\sigma] = [Q][\epsilon]$:

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_{12} \end{bmatrix} = \begin{bmatrix} 92050 & 4610 & 0 \\ 4610 & 92050 & 0 \\ 0 & 0 & 3600 \end{bmatrix} \begin{bmatrix} -2.525 \times 10^{-3} \\ 2.03 \times 10^{-4} \\ 0 \end{bmatrix} = \begin{bmatrix} -231.5 \\ 0.004 \\ 0 \end{bmatrix} \tag{17}$$

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_{12} \end{bmatrix} = \begin{bmatrix} 92050 & 4610 & 0 \\ 4610 & 92050 & 0 \\ 0 & 0 & 3600 \end{bmatrix} \begin{bmatrix} 2.42 \times 10^{-3} \\ -4.4 \times 10^{-5} \\ 0 \end{bmatrix} = \begin{bmatrix} 222.55 \\ 7.1 \\ 0 \end{bmatrix} \tag{18}$$

The compressive strength of the material in x direction is -493MPa. Thus, according to maximum stress theory, as 231.5< 493, the lamina is safe under the given loading. The factor of safety is 2.13.

The tensile strength of the material in x and y direction is 829MPa. Thus, according to maximum stress theory, as 222.55<829 and 7.1<829, the lamina is safe under the given loading. The factor of safety is 3.72. Hence, the structure is safe for given loading conditions, and factor of safety is 2.13. The original thickness of the spokes was 40mm, and it was changed to 30 mm, and hence there is a reduction of 25% of the weight of the spokes.

The center hub of the wheel is made of aluminium alloy for ease of attachment to existing cars. The composite wheel rim and spokes are attached to the aluminium center using Hysol 9309.3NA, an epoxy adhesive. This epoxy is chosen for its high strength and because it contains small glass beads that provide good bondline thickness control. In order to determine that there is sufficient bond surface area for the adhesive, the following calculations are done [2]: Torsion causes shear in the bond. The torsion load is 4281.2 Nm. Thus, the shear force is 4281.2/0.08 = 53515N. The shear strength of the adhesive is 28.9 MPa. The minimum area required for bonding is thus 53515/28.9 = 2475 mm^2 = 0.002475 m^2. The total bonding area available is 0.05 m^2. Hence, the design is safe.

5. Results and discussion

The final design of the hoop is as follows: Epoxy Carbon UD (395 GPa) Prepreg with the 0^0 direction along circumference of the hoop, and 90^0 axially. The laminas are stacked in the following sequence: 5±45° woven lamina, 3 90^0 lamina, 3 0^0 lamina, 3 90^0 lamina and 5±45° woven lamina. Thus, total thickness is 3.8mm (0.2mm for each layer). Thus, the original 10 mm thickness hoop weight is reduced to about 40%. The spokes are designed with Epoxy Carbon Woven (395GPa) Prepreg and the 0^0 fibers in the radial direction, 90^0 in the axial direction and 250 laminas of 0.2 mm thickness. The center part of the wheel is made of aluminium alloy so that the existing wheels in the cars can be easily replaced by the newly designed wheel.

6. Conclusion

By replacing the aluminium alloy by CFRP, there is reduction of weight in the spokes and the rim because of the low densities of Epoxy Carbon UD (395 GPa) Prepreg (1540kgm^{-3}) and Epoxy Carbon Woven (395GPa) Prepreg (1480 kgm^{-}3) to that of aluminium alloy(2770kgm^{-3}). Also, the composite wheel is designed such that excess material is not used, and thus due to better strength of the material the mass is further reduced. For the hoop, 7.3(original mass)*0.55(due to CFRP weight)*0.4(due to CFRP Design) = 1.61 kg. For the spokes, 9.11(original mass)*0.55(due to CFRP weight)*0.75(due to CFRP design) = 3.76 kg. Thus, the total mass of the new wheel is 2.55(hub) + 3.76(spokes) +1.61(hoop) = 7.92kg. The new designed wheel is thus 42% in weight of the original. Thus, the objective of reduction in mass of the wheel has been achieved. For the considered vehicle, this wheel will provide a better driving performance and increase the travelling range of the vehicle. In the future, studies can be done to physically test the designed wheel in various conditions for further improving thedesign.

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