Design, Manufacturing & Testing of Composite Gear in Powertrain of an Off-Road Vehicle

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Abstract –

Due to its substantial strength and dependability, ferrous materials are commonly used in the automotive industry while also compromising on weight. To improve the vehicle's performance in terms of vibration, acceleration, and damping, lighter materials with higher strength than steel and approximately equivalent reliability can be employed. Carbon Fiber composite materials are roughly 78 percent lighter than ferrous alloys and have better strength per unit volume than steel. Metals with carbon fiber composites can be used in automobile gears to disrupt the vibration transmission pathway from the gear teeth to the center of the shaft, reducing total noise and weight without sacrificing load capacity. Carbon fiber composites directional characteristics are studied because of their anisotropic nature. Because of its greater torsional rigidity and impact strength, this material is suitable for drive shafts that must endure torsional forces, as well as suspension links that are subjected to fatigue loading. The goal of this project is to investigate the directional properties of carbon fiber composite materials, develop, analyse, and produce metal-carbon fiber composite gears, drive shafts, and suspension links, and test the product's and epoxy adhesive's long-term viability.

***Key Words*: Carbon fiber composites, fatigue loading, gears, epoxy adhesives.**

1. INTRODUCTION

The advent of the technology era has necessitated the development of new materials to address the day-to-day issues of existing materials for varied purposes, and in the search for new advanced materials, researchers have developed a variety of material systems Metal matrix composites (MMCs) have been utilized to build new materials for several decades. By creating composites, it is possible to leverage specific benefits of two or more elements distinct parts working together to overcome each other's limitations constituents. Steel, aluminium, and titanium are traditional materials that are failing to meet the problems that common materials face today. We will unveil the utilisation of carbon fiber composites in automobile applications in future studies. Research into carbon fiber, adhesives, and the influence of carbon fiber orientation on its strength employing the different software's, as well as experimental validation. For the first time in 1860, Joseph Swan created carbon fiber for use in light bulbs. In 1879, Thomas Edison carbonised cotton threads or bamboo slivers by baking them at high temperatures, creating the first all-carbon fiber filament. Electricity will be used to heat incandescent light bulbs. Lewis Latimer came up with the idea around 1880 for incandescent light bulbs, a durable carbon wire filament, heated by electricity. The Japanese seized the lead in producing PAN-based carbon fibers in the late 1960s. 1970 joined technology agreement allowed union carbide to manufacture japans Toray industries products. Morganite decided that making carbon fibers was a good idea. Courtaulds is the only major UK manufacturer that is not ancillary to its core business. Courtelle's water-based inorganic technique left the product susceptible to contaminants that did not impact other carbon-fiber manufacturers' organic processes, prompting Courtaulds to stop producing carbon fiber in 1991. Moreover, throughout this time, the Japanese government has been a strong supporter of carbon fiber research and development both at home and abroad. Toray, Nippon Carbon, and Toho Rayon are just a few of the Japanese companies involved. Carbon fiber from Toray, Celanese, and Akzo made their way from secondary to primary parts in aerospace, first in military aircraft and then in civil aircraft like McDonnell Douglas. Planes made by Boeing and Airbus. A composite material is one that is made up of at least two different materials. At least two elements interacting to provide material qualities that differ from one another the characteristics those elements on their own. In practice, most composites are made up of a bulk material (the "matrix") and some form of reinforcement, which is added to boost the matrix's strength and stiffness. Fiber is the most common type of reinforcement form. The most prevalent man-made composites nowadays can be classified into three categories. Polymer Matrix Composites is a group of polymer matrix composites (PMCs). These are the most prevalent, and they will be the focus of this article. Fiber Reinforced Polymers (or Plastics), sometimes known as FRP, are materials that use a polymer-based resin as a matrix and a range of fibers to reinforce it .Glass, carbon, and aramid fibers are used as reinforcement.

2. Problem Statement

ATVs (All Terrain Vehicles) are designed for tough terrain. As a result, it's necessary to design critical components with extreme caution and safety. Plain carbon steels with adequate strength are utilized in automotive transmission systems (gears) which have sufficient strength to withstand the direct contact and fatigue stresses to which the gear is subjected for the rest of its life. However, due to restrictions in the qualities of the materials currently employed for this purpose, the transmission unit's performance and life decline after a given period of time. High rotational Inertia, and lower damping characteristics of the materials are used in traditional gears (plain carbon steel) that have a significant impact on the vehicle's performance and the gearbox shaft. As a result, there is a chance to develop a superior alternative material with higher damping, better mechanical qualities, and low inertia.

3. Material Comparison

The comparisons that follow show a range of mechanical properties for the composite materials. The lowest properties for each material are associated with simple manufacturing processes and material forms (e.g. spray lay-up glass fiber), and the higher properties are associated with higher technology manufacture (e.g. autoclave moulding of unidirectional glass fiber prepreg), such as would be found in the aerospace industry.

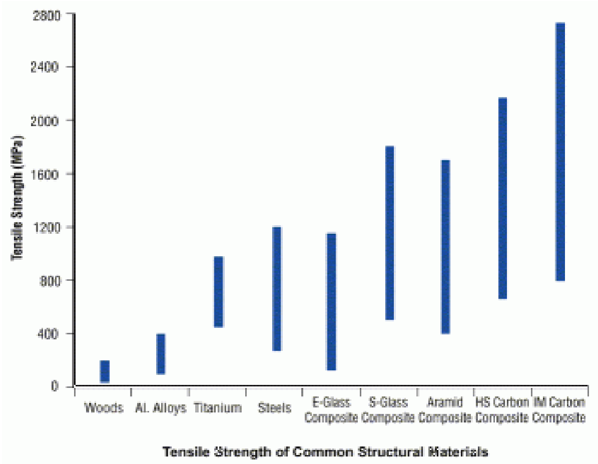

Chart 1- Tensile Strength of common structural materials

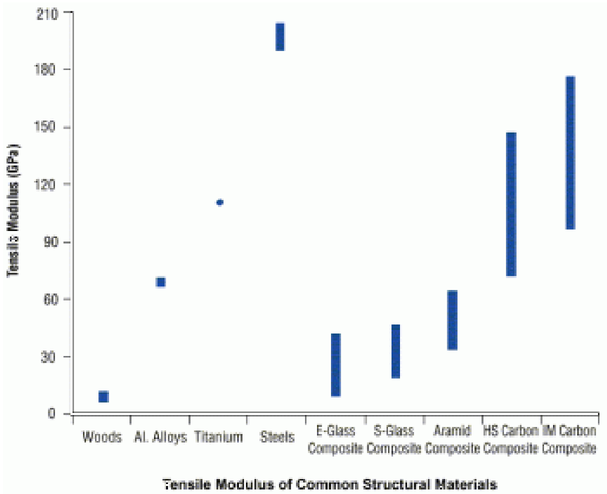

Chart 2- Tensile modulus of common structural materials

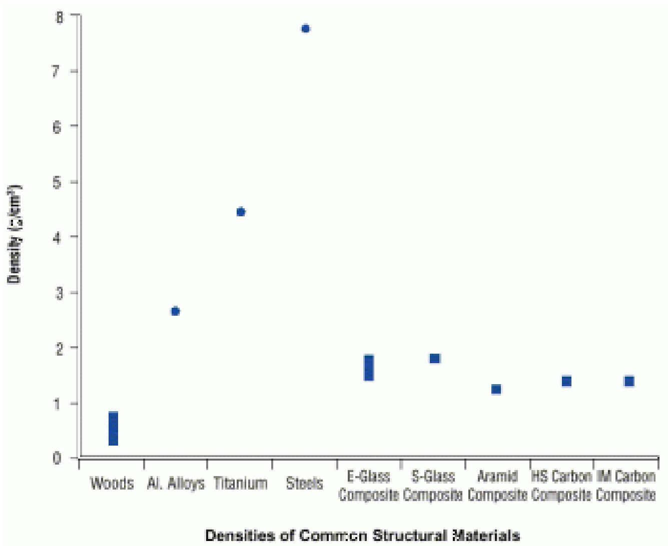

Chart 3- Densities of common structural materials

The Charts 1, 2 and 3 clearly show the range of properties that different composite materials can display. These properties can best be summed up as high strengths and stiffnesses combined with low densities. It is these properties that give rise to the characteristic high strength and stiffness to weight ratios that make composite structures ideal for so many applications. This is particularly true of applications which involve movement, such as cars, trains and aircraft, since lighter structures in such applications play a significant part in making these applications more efficient.

4. Ideology

Gears are subjected to periodic stresses of high magnitude. To withstand these stresses the materials for the gears are carefully selected and design is based on the manufacturing process used which limit the types of materials that can be used for these drive elements. Generally Plain carbon steels due to their suitable tensile properties, high machinability and hardenability are used for the gear drives. Gear tooth are subjected to direct contact stresses and fatigue loading in case of automobile transmission. Hence it is not feasible to use the material other than plain carbon steels for the toothed rim of the gear. The hub portion of the gear is to be fitted on the shaft with carefully calculated limits, fits and tolerance. Steel materials can be given proper fits by grinding method which is not that easy for other materials of similar strength. Hence it becomes mandatory for us to use conventional gear materials. However, the portion of the gear in between the Rim and Hub is not subjected to direct contact stresses nor it has any machining constraints. Hence this portion of steel can be replaced by material other than that of steel which would improve the overall performance and life of the gear. A carbon fiber composite as discussed in earlier section is suitable for this section requirement and would have positive impact on the overall working of the transmission unit. Following figures used for the portion between the hub and rim.

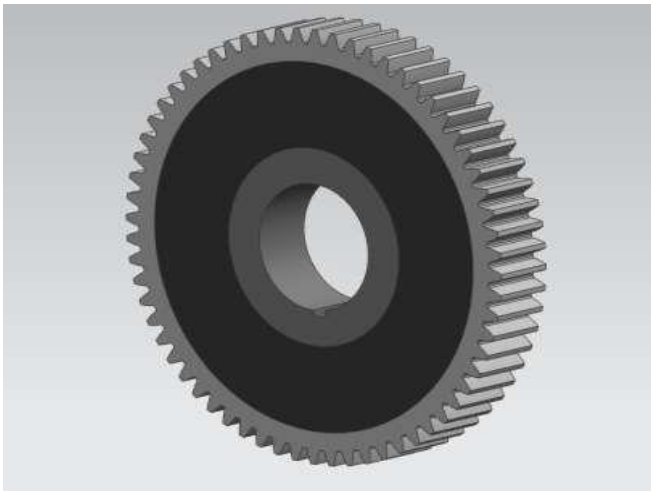

Fig.1: Circular Hub and Rim model

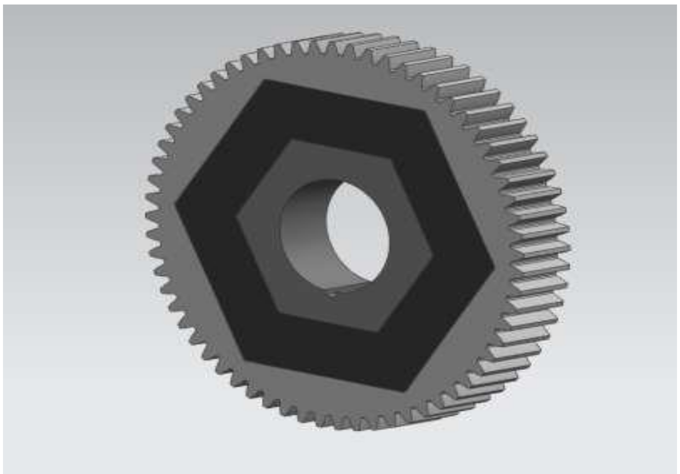

Fig.2: Hexagonal Hub and Rim Model

Figure 1: Reveals the basic idea of the concept how the carbon fiber can be implemented for the required application. It consist of a cylindrical hub with circular cross section. The carbon fiber composite is bounded to the hub by using adhesive of suitable shear strength. The toothed rim and composite material is further bounded by the same adhesive. The strength of this configuration entirely depends on the shear strength of the adhesive and in case of failure of the adhesive the entire system fails and stops the transmission unit.

Figure 2: Reveals another configuration in which cylindrical hub with hexagonal cross section is used. The bonding of Hub-composite and composite-rim is done by the same adhesive as used in the previous case. The advantage of this configuration is that it provides positive locking between the metal and composite which provides additional shear strength than that obtained by just using the adhesive. Hence

model in figure 2 can be selected for the application of the gear.

4.1 Analytical Approach

The above concept is used in the constant reduction gearbox of an ATV. The last gear of the geartrain is subjected to the maximum torque of 570 N-m considering all the safety and impact factors

Force acting on the hub-composite interface,

F1=T/R1

Where, F1= Shear force acting at hub- composite interface

R1= Radial distance of interface from the shaft center= xyz

T= Max. torque acting on the gear

F1= 570000/21 = 27142.85 N (I)

Force acting on the composite-Rim interface,

F2=T/R2

Where, F2= Shear force acting at composite-Rim interface

R2= Radial distance of interface from the shaft center= xyz

T= Max. torque acting on the gear

F2= 570000/ 65 = 8769.23 N (II)

From equation (I) & (II) it can be seen that force acting at Hub- composite interface is greater than that of composite-Rim interface (F1>F2).

This implies that maximum shear stress is at Hub- composite interface which ultimately proves that it is not necessary to use the configuration in fig.2 for composite-rim interface.

The configuration will be as per Fig. 3

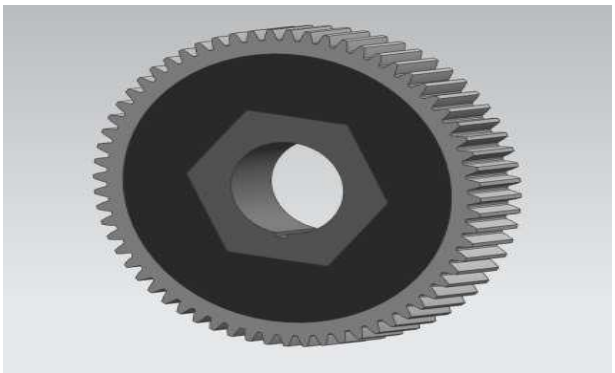

Fig.3 : Hexagonal Hub and Circular Rim Model

4.2 Design Consideration:

i) The properties of the fiber

ii) The properties of the resin

iii) The ratio of fiber to resin in the composite (Fiber Volume Fraction)

iv)The geometry and orientation of the fibers in the composite

4.3 Filament Winding

Carbon fibers obtained after processing Polyacrylonitrile (PAN) which is wound on steel hub and processed at specific temperature and specific time. The process of winding the fiber on the hub is known as filament winding. Before designing the composite gear it is necessary to understand the concept of carbon fiber filament laminates, its directional properties and its advantages.

Following are some of the characteristics of filament winding,

1. High strength to weight ratio is possible to achieve with this process.

2. High degree of uniformity in fiber distribution, orientation and placement.

3. Labor involvement is minimal as it is an automated process.

4. Filament winding method is suitable to process composite parts requiring precise tolerances.

5. Fiber orientation in a specific direction is possible in this process.

6. Cost of the composite part processed through filament winding method is substantially low as compared to other manufacturing methods as this process involves less and low cost material to produce high strength component.

Considering the above properties of the composites it is necessary to select the correct `winding angle for the filaments that would bear the tangential loads on the section between the hub and rim. Filament winding is done at specific angles depending on the applications.

Fig.4 shows the filament winding at any other angle other than 90 degrees

Fig.5 shows the filament winding at 90 degree angle.

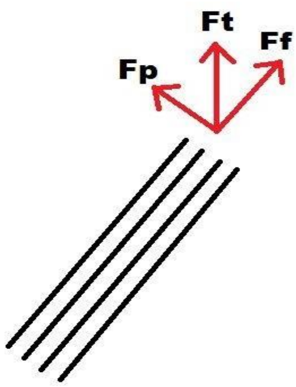

Fig.4 : Oblique winding

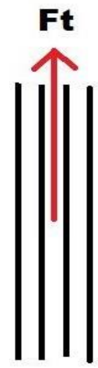

Fig.5 : Hoop Winding

In fig.4 we can see that the components of tangential force act along the direction of fibers as well as in the direction perpendicular to it. While in the fig. 5 the complete tangential force acts along the fibers. The directional properties of carbon fiber composites reveal that it has high load bearing capacity in the direction of fibers than that in the direction perpendicular to the fibers. Hence we use hoop winding (winding at 90 degrees) for the composite material used in gear which is subjected to tangential force.

5. Matrix and Reinforcements:

Carbon fiber's characteristics alone are insufficient to meet the application's functional requirements. Carbon fiber composites have two phases: matrix and reinforcement. Carbon fiber reinforced plastics (CFRPs) are a type of composite material. The composite in this scenario is made up of two parts: a matrix and reinforcement. Carbon fiber is used as a reinforcement in CFRP to enhance strength. To bind the reinforcements together, the matrix is commonly a polymer resin, such as epoxy. The material properties of CFRP are dependent on these two aspects because it is made up of two separate constituents.

5.1 Mechanical Properties:

The stress/strain curve for a 'perfect' resin system is shown in figure 6.This resin's curve demonstrates strong ultimate strength, stiffness (as indicated by the first gradient), and strain to failure. This indicates that the resin will be stiff at first but will not suffer brittle failure.

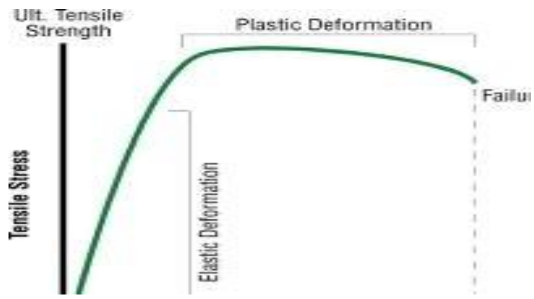

Fig.6 : Mechanical properties of composites

5.2 The Resin System's Adhesive Properties

Any resin system requires a high level of resin-to-reinforcement fiber adhesion. This will ensure that the loads are efficiently transferred and that there is no cracking or fiber/resin debonding when the system is stressed.

5.3 Toughness Properties of the Resin System

Toughness is a measure of a material's resistance to crack propagation, however it can be difficult to precisely quantify in a composite. The stress/strain curve of the resin system, on the other hand, gives some indication of the material's toughness on its own. The more deformation a resin can withstand before failing, the stronger and more crack-resistant the material becomes.

5.4 Environmental properties of resin system:

Any resin system must have good resistance to the environment, water, and other aggressive substances, as well as the ability to sustain frequent stress cycling. These characteristics are especially relevant in a marine environment.

5.5 Selection of adhesives:

As discussed earlier the resins can be used as adhesives for bonding hub-composite- rim. The calculation of stresses induced on the metal composite interface helps in the selection of appropriate adhesive.

Shear stress on the metal composite interface can be given by the following equation $\tau = T/(R*A)$

where , τ= shear stress,

T= torque on the gear= 570000 N-mm

R= radial distance of interface from shaft center (mm)

A= Surface are on metal composite interface (mm^2) Shear stress on the hub-composite interface is as follows, R=21mm

A= pi*42*24

T=570000

τmax = 8.57 MPa

Max shear stress= 8.75 MPa

Shear stress on the composite- rim interface.

R=65mm

A= pi*130*24

T=570000

τmax = 0.89MPa

Max shear stress= 0.89MPa

From the above results it can be concluded that the maximum shear stress to which the adhesive is subjected is 8.75, then we should select the adhesive having shear strength greater than 8.75. Epoxy Loctite 9430 adhesive is easily available adhesive and interlaminar shear strength of 29.05Mpa [5]. Hence at the preliminary stage this adhesive was selected. The torsion testing of the prototype will further ensure the use of this adhesive.

5.6 Curing Temperature and curing time

Uncured epoxy resins are characterised by low mechanical, chemical, and heat resistance. However, by reacting the linear epoxy resin with appropriate curatives to generate three-dimensional cross-linked thermoset structures, acceptable characteristics can be attained. The term "curing" or "gelation" is used to describe this process. Curing epoxy resins is an exothermic and, in some situations, protothermic reaction. If not controlled, produces enough heat to cause thermal deterioration. Curing can be accomplished by reacting one epoxy with another epoxy (homopolymerisation) or by producing a copolymer with polyfunctional cures or hardeners. In theory, any molecule possessing a reactive hydrogen can react with the epoxy resin's epoxide groups. Amines, acids, acid anhydrides, phenols, alcohols, and thiols are examples of common epoxy resin hardeners. While certain epoxy resin/hardener combinations cure at room temperature, many others require heat, with temperatures as high as 150°C. Inadequate heat during cure will result in an incompletely polymerized network, resulting in lower mechanical, chemical, and heat resistance. To get maximal characteristics, the cure temperature should typically reach the completely cured network's glass transition temperature (Tg). To manage the rate of curing and avoid excessive heat build-up from the exothermic reaction, the temperature is occasionally increased in steps. Latent hardeners are hardeners that have minimal or limited reactivity at ambient temperatures but react with epoxy resins at increased temperatures. When employing latent hardeners, the epoxy resin and hardener can be mixed and held for a period of time before being used, which is useful in a variety of industrial processes. One-component (1K) products can be made with very latent hardeners, in which the resin and hardener are provided pre-mixed to the end user and only heat is required to commence curing. One-component products have shorter shelf life than traditional two-component systems, and they may require chilled storage and transportation. The epoxy curing reaction can be sped up by using modest amounts of accelerators. This decision is made based on the resin's availability. The prototype will be used after it has been tested.

6. ANALYSIS OF COMPOSITE GEAR:

The carbon fiber composite gear is analysed by using software i.e. ANSYS WORKBENCH 18.1. the gear is divided into three separate components Hub, Rim and Carbon fiber and the analysis is performed separately for each component as we have seen above the using an adhesive, in order to determine the shear stresses on these interfaces we used FEA software and validate use of adhesive which has shear strength greater than that of the shear stress induced on these interfacial surfaces. All the three parts are analyzed for the torsional shear stress acting on them by performing static structural analysis.

6.1 Analysis of metallic hub:

As finalized in design the metallic hub of hexagonal shape was chosen for this application. It is to be analyzed for the shear stress acting on its outer surface i.e. on the carbon fiber and hub interface.

Boundary conditions:

i) Fixed support at inner surface.

ii) Twisting moment of 570 Nm on the outer surface.

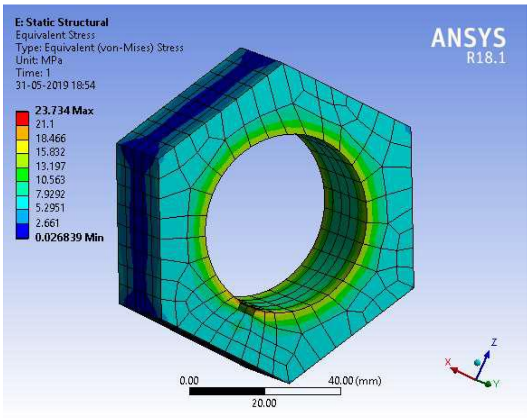

Fig.7: Equivalent stress on Hub

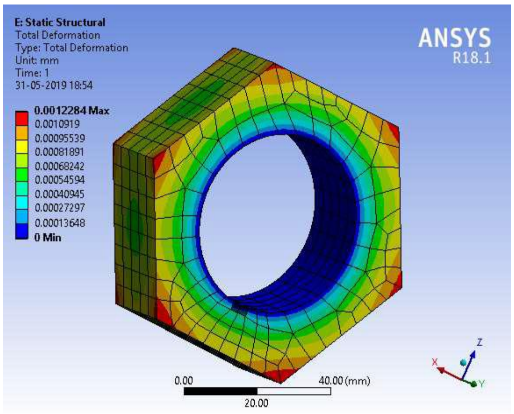

Fig.8: Maximum deformation on Hub

As shown in the Fig 7 and Fig 8, the shear stress on the outer surface of the hub is 23.734 MPa. The inner laminar shear strength of the adhesive is 56-57 MPa. Hence from the results it can be concluded that use of adhesives for these applications is safe.

6.2 Analysis of metallic Rim:

As finalized in design the metallic rim of circular inner surface was chosen for this application. It is to be analyzed for the shear stress acting on its circular inner surface i.e., on the carbon fiber and rim interface

Boundary conditions:

i) Fixed support at outer surface.

ii) Twisting moment of 570 Nm on the inner surface.

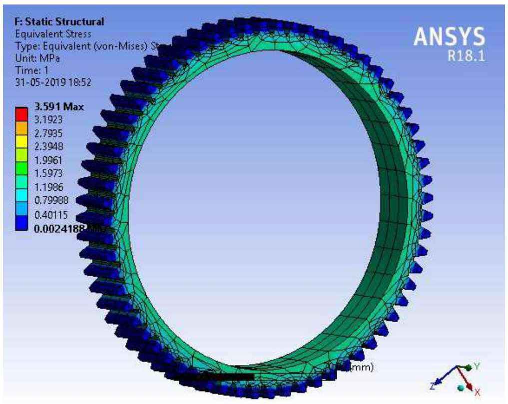

Fig.9: Equivalent stress on Rim

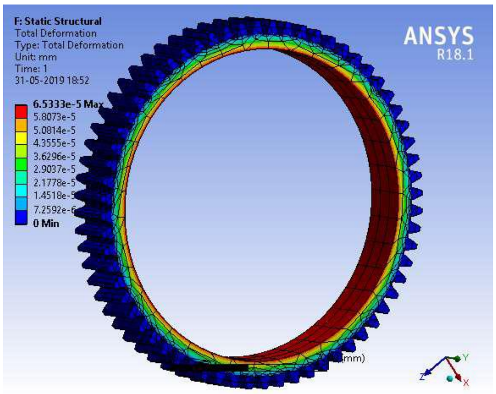

Fig.10: Maximum deformation on Rim

As shown in Fig 9 and Fig 10, the shear stress on the inner surface of the rim is 3.591 MPa. The inner laminar shear strength of the adhesive is 57-67 MPa. Hence from the results it can be concluded that use of adhesives for these applications is safe.

6.3 Analysis of CFRP:

As carbon fiber reinforced polymer is anisotropic in nature. It is to be analyzed for the different orientation of fiber and the orientation with minimum deformation is to be chosen. As discussed in section 10 the perpendicular winding subjected to negligible transverse force as compared to oblique winding. So it is necessary to validate the use of perpendicular winding for the required application

6.3.1 Analysis for oblique winding:

Preparation of model:
The carbon fiber part with its material orientation and directional properties need to be created in software. This model with assigning material. The geometry is created in Ansys Module and then meshed in Ansys Mechanical. The

geometry is then imported in ACP geometry is arranged in the form of winded layers. In each layer the fibers are wound at angle of 45 degree with the axis of gear. The alternate layers of fibers and epoxy were generated. All the layers are combined to form the model of the part.

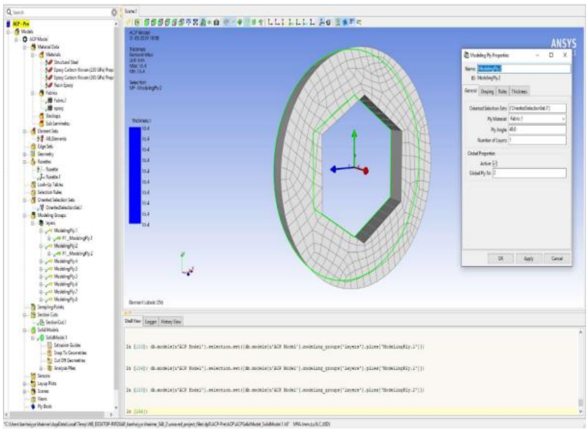

Fig 11: Model preparation of obliquely winded CFRP in ACP (pre)

Boundary conditions:

As seen in the above analysis the shear stress decreases with increase in radial distance from the Centre so as the CFRP is subjected to maximum shear stress at inner surface. The deformation at this surface is to be checked; hence it is fixed at outer surface. The twisting moment of 570 Nm is applied at the inner surface.

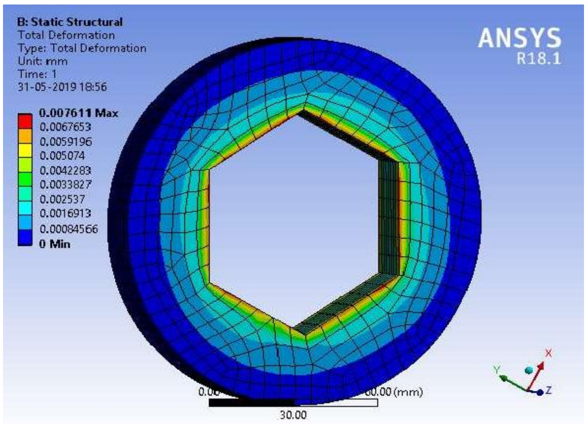

Fig. 12: Maximum deformation on carbon fiber part

As shown in Fig 11 and Fig 12, the maximum deformation for the CFRP with oblique winding is 0.007 mm.

6.3.2 Analysis for perpendicular winding

Preparation of model:

The method for preparation of model is same as that for oblique winding. The geometry is arranged in the form of winded layers. In each layer the fibers are wound at angle of 90 degree with the axis of gear. The alternate layers of fibers and Epoxy were generated. All the layers are combined to form the model of the part shown in Fig.13.

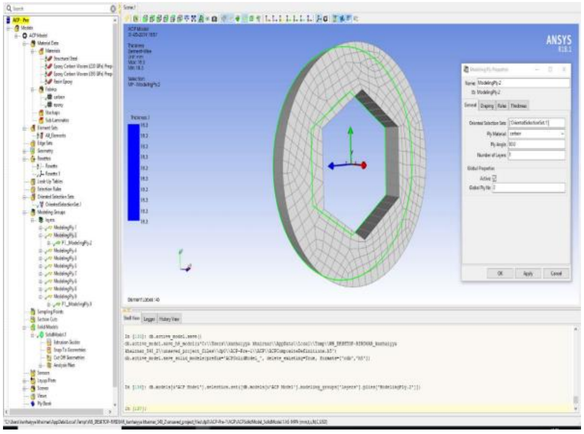

Fig.13: Model preparation of perpendicular winded CFRP in ACP (pre)

Boundary conditions:

i) Fixed support at the outer surface.

ii) Twisting moment of 570 Nm at inner surface.

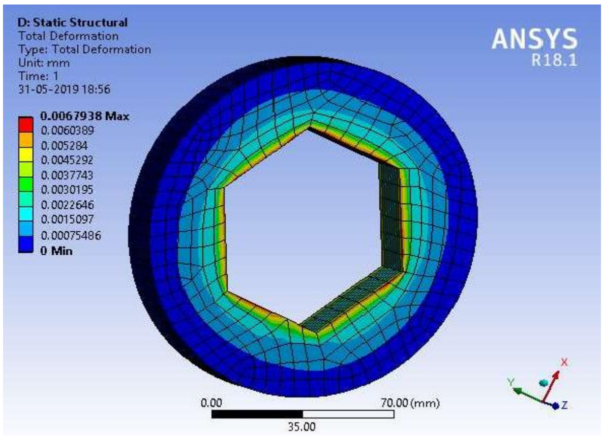

Fig.14: Maximum deformation on carbon fiber part

As shown in Fig.14, the maximum deformation for the CFRP with oblique winding is 0.006 mm. As the deformation for the perpendicular winded CFRP is less than the obliquely winded CFRP, it confirms that the use of former is suitable and safe for the required application.

7. Conclusion

Thus the study of Carbon fiber composite material was performed in order to design the Carbon fiber composite gear. Understanding the concept and effect of orientation and directional properties of the fibers and the adhesion properties of epoxy the design of gear was completed. It was validated with the help of FEA software. The use of proper orientation and type of adhesive was proved to correct by the analysis. This confirms the use of gear in automotive transmission (ATV).

8. Future Scope

The carbon fiber composite gear can be used in racing or formula cars to reduce the weight of transmission system and hence improve the acceleration performance. The transmission components with higher durability and lower vibrations and noise can be designed by using the proposed concept. Materials other than carbon fiber can also be used in composite gears due to which the rotational inertia of the system will decrease. Cost of carbon fiber is the major disadvantage of the concept. The fiber preparation at lower cost and easy method of impregnation process will reduce the overall cost of the CFRP. This can be the future target for most of the automotive and aero based industries aiming to use the proposed idea.

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