Finite Element Analysis and optimization of Automotive Composite Drive Shaft

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Abstract— **Almost all automobiles (at least those which correspond to design with rear wheel drive and front engine installation) have transmission shafts. The weight reduction of the drive shaft can have a certain role in the general weight reduction of the vehicle and is a highly desirable goal. Substituting composite structures for conventional metallic structures has many advantages because of higher specific stiffness and strength of composite materials. The advanced composite materials such as graphite, carbon, Kevlar and Glass with suitable resins are widely used because of their high specific strength and high specific modulus. Advanced composite materials seem ideally suited for long power driver shaft applications. The automotive industry is exploiting composite material technology for structural components construction in order to obtain the reduction of the weight without decrease in vehicle quality and reliability. It is known that energy conservation is one of the most important objectives in vehicle design and reduction of weight is one of the most effective measures to obtain this result. Actually, there is almost a direct proportionality between the weight of a vehicle and its fuel consumption, particularly in city driving. The present work includes, analysis done on drive shaft of Toyota quails with different composite materials and concludes that the use of composite materials for drive shaft would induce less amount of stress which additionally reduces the weight of the vehicle. In present work, analysis done on dive shaft with different composite materials and concludes that the use of composite materials for drive shaft would induce less amount of stress which additionally reduces the weight of the vehicle.**

Keywords—**Reinforced polymer composites, Laminated composite, Drive shaft.**

I. INTRODUCTION

Composite materials are commonly used in structures that demand a high level of mechanical performance. Their high strength to weight and stiffness to weight ratios has facilitated the development of lighter structures, which often replace conventional metal structures. Rapid technological advances in engineering design field result in finding the alternate solution for the conventional materials. The design engineers brought to a point to finding the materials which are more reliable than conventional materials. Researchers and designers are constantly looking for the solutions to provide stronger and durable materials which will answer the needs of fellow engineers. Drive shafts are used as power transmission tubing in many applications, including cooling towers, pumping sets, aerospace, trucks and automobiles. In the

design of metallic shaft, knowing the torque and the allowable shear stress for the material, the size of the shaft's cross section can be determined. In the today's days there is a heavy requirement for lightweight materials vehicle. The conventional steel material is replaceable by advanced composite materials. Composite materials are favored by most of the scientist in the design of automobiles due to its higher specific strength and stiffness. Weeton *et al*. [1] stated the possibilities of replacing the conventional steel material by composites in the field of automobile. Weeton *et al* describe the possibilities of composites used to replace the steel leaf spring as well as steel drive shaft. The advanced composite materials such as graphite, carbon, Kevlar and glass with suitable resins are widely used because of their high specific strength (strength / density) and high specific modulus (modulus / density). The first application of composite drive shaft to automotive was the one developed by Spicer U-joint divisions of Dana Corporation for the Ford econoline van models in 1985. Drive shafts for power transmission are used in many applications, including cooling towers, pumping sets, aerospace, structures, and automobiles.

In metallic shaft design, knowing the torque and the allowable service shear stress for the material allows the size of the shaft's cross-section to be determined. Beard more et al. [2] is also states the potentials of composites in structural applications. Conventional steel drive shafts are manufacture in two pieces to increase its fundamental natural bending frequency. The conventional assembly of drive shaft is made up in two pieces and joined together by u-joints due to which the overall weight of the assembly is increased. The composite drive shaft [3] has advantages like considerable weight reduction, symmetric composite assured the dynamic balance of increasing operating speed, electrically nonconductive, custom end fitting considerations, vibrations and harshness (NVH), long fatigue life and also it reduce the bearing & journal wear.

II. DESIGN OF COMPOSITE DRIVE SHAFT

a. Specification of the problem

The fundamental natural bending frequency for passenger's cars, small trucks and vans of the propeller shaft should be higher than 2,400 rpm to avoid whirling vibration and the torque transmission capability of the drive shaft should be larger than 154 Nm. The drive shaft outer diameter should not exceed 100 mm due to space limitations.

The torque transmission capability of the drive shaft is taken as 151 N.m the length and the outer diameter here are considered as 1.5 meters and outer diameter of the shaft is 0.072, respectively. The drive shaft of transmission system was designed optimally to meet the specified design requirements [4].
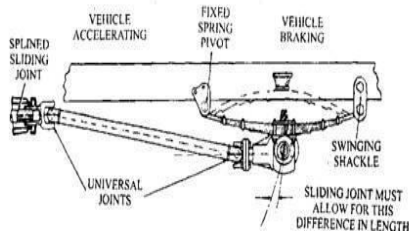

Figure 1: Drive Shaft Arrangement in automobiles

b.   Assumptions

The shaft rotates at a constant speed about its longitudinal axis. The shaft has a uniform, circular cross section. The shaft is perfectly balanced, all damping and nonlinear effects are excluded. The stress-strain relationship for composite material is linear and elastic; hence, Hook's law is applicable for composite materials. Since lamina is thin and no out-of-plane loads are applied, it is considered as under the plane stress [5].

c.   Demerits of Conventional Drive Shaft
- They have less specific modulus and strength
- Increased weight
- Conventional steel drive shafts are usually manufactured in two pieces to increase the fundamental bending natural frequency because the bending natural frequency of a shaft is inversely proportional to the square of beam length and proportional to the square root of specific modulus. Therefore the steel drive shaft is made in two sections connected by a support structure, bearings and U-joints and hence overall weight of assembly will be more.
- Its corrosion resistance is less as compared with composite materials.
- Steel drive shafts have less damping capacity.

d.   Merits of Composite Drive Shaft

- They have high specific modulus and strength.
- Reduced weight.
- The fundamental natural frequency of the carbon fiber composite drive shaft can be twice as high as that of the steel or aluminum because the carbon fiber composite material has more than 4times the specific

stiffness of, which makes it possible to manufacture the drive shaft of passenger cars in one piece. A one-piece composite shaft can be manufactures so as to satisfy the vibration requirements. This eliminates all the assembly, connecting the two piece steel shafts and thus minimizes the overall weight, vibrations and cost.

- Due to weight reduction, fuel consumption will be reduced.
- They have high damping capacity and hence they produce less vibration and noise.
- They have good corrosion resistance.
- Greater torque capacity than steel and aluminium shaft.
- Longer fatigue life than steel and aluminium shaft.

e.   Theoretical and ansys results simulation

The drive shaft for simplicity has been first idealized as a hollow cylindrical shaft which is fixed at one end and on other end which a torque of 151Nm is applied as represented below [6]

III.   MODELING OF DRIVE SHAFT

The modeling steps of universal joint in CATIA V5 are briefly discussed here. First an arbitrary plane is selected and sketcher workbench in sketcher toolbar is invoked. Then the sketch shown in the figure 2 is drawn with appropriate dimensions and corners are filleted with radius of 5mm by invoking corner command in operation toolbar. Then the sketch is padded for 8mm by invoking pad command in sketch based features after exiting from the sketcher workbench.

The modeling steps of centre block in CTAIA V5 are briefly discussed here. First an arbitrary plane is selected and sketcher workbench in sketcher toolbar is invoked. Then a circle of 10mm diameter is drawn using drawing tools and sketcher is exited. Now the circle is padded about 36mm on both sides using pad command in sketch based features toolbar. Again the same plane is selected and entered into the sketcher to draw a circle of 23mm diameter. This circle is also padded about 19mm in both sides by invoking pad command in the sketch based features toolbar. Above three operations are repeated in any other plane which is perpendicular to the previously selected plane. Now the plane which is selected initially is selected and sketcher is invoked. A sketch as shown in the figure 2 is drawn. And this sketch is pocketed towards the centre block up to 12mm by invoking the pocket command in sketch based features toolbar. The edges are filleted about 5mm by invoking edge fillet command in dress-up features toolbar. The above two steps are mirrored by invoking mirror command in transformation features toolbar. Thus the centre block is modeled and is shown in the figure 2.

The modeling steps of propeller shaft in CTAIA V5 are briefly discussed here. First an arbitrary plane is selected and sketcher workbench in sketcher toolbar is invoked. A circle of

diameter 75mm is drawn and is padded by invoking pad command in sketch based features toolbar. The side view of the shaft is made as the working plane and the sketch shown in the figure 2.is drawn by projecting required edges using project 3D command in operation toolbar. This sketch is padded about 22.5mm on both sides using pad command in sketch based features toolbar. Now tritangent fillet is applied on both the yokes as shown in the figure 2. The same tritangent fillet is made use to obtain the contour between the yokes. And the circular projections are obtained by invoking particular plane as working plane, drawing circles of diameters 28mm and 23mm and then finally padding about 2mm each by invoking pad command in sketch based features toolbar. This is shown in the figure 2.
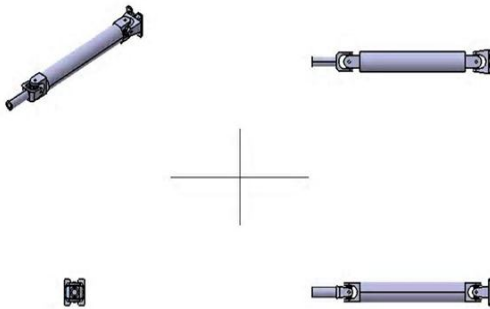
Figure 2: various views of drive shaft

IV. FINITE ELEMENT ANALSYS

The finite element analysis is a numerical technique for finding approximate solutions of partial differential equations as well as of integral equations. The solution approach is based on either eliminating the differential equation completely (steady state problems) or rendering the partial differential equation into an approximating system of ordinary differential equations, which are then numerically integrated using standard techniques such as Euler's method, Runge-Kutta method etc.,

In the finite element method, a structure is broken down into many small simple blocks or elements. The behavior of an individual element can be described with a relatively simple set of equations. Just as the set of elements would be joined together to build the whole structure, the equations describing the behaviors of the individual elements are joined into an extremely large set of equations that describe the behavior of the whole structure.

The following steps summarize the general procedure for finite element analysis.

Step 1 - The continuum is a physical body, structure or solid being analyzed. Discretization may be simply described as process by which the given body is subdivided into equivalent system of finite elements.

Step 2 - The selection of displacement or temperature models or shape functions representing approximately the actual distribution of the displacement or temperature. The three factors which influence the selection of shape functions are

- The type and degree of displacement model

- Displacement magnitudes

- The requirements to be satisfied which ensuring correct solution.

Step 3 - The derivation of the stiffness matrix which consists of the coefficients of the equilibrium equations derived from the geometric and material properties of the element. The stiffness relates the displacement at nodal points to applied forces at nodal points.

Step 4 - Assembly of the algebraic equations for the overall discredited continuum includes the assembly of overall stiffness matrix for the entire body from individual element stiffness matrices and the overall global load vector from the elemental load vectors.

Step 5 - The algebraic equations assembled in step 4 are solved for unknown displacements by imposing the boundary conditions. In linear equilibrium problems, this is a relatively straightforward application of matrix algebra techniques.

Step 6 - In this step, the element strains and stresses are computed from the nodal displacements that are already calculated from step 5.
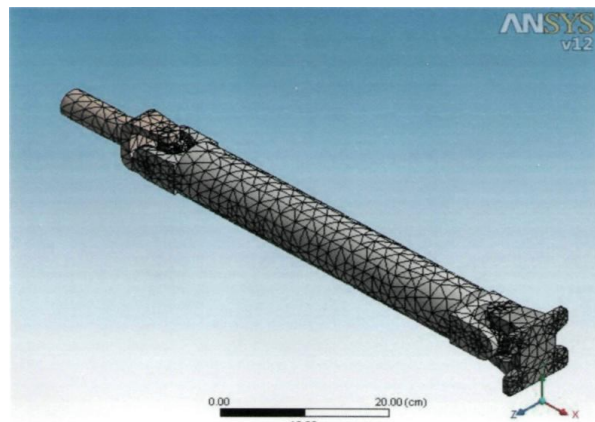

Figure 3: Meshed model of drive shaft

a. Advantages of ANSYS

ANSYS provides a cost-effective way to explore the performance of products or processes in a virtual environment. This type of product development is termed virtual prototyping. With virtual prototyping techniques, users can iterate various scenarios to optimize the product life before the manufacturing is started. This enables a reduction in the level of risk, and in the cost of ineffective designs. The multifaceted nature of ANSYS also provides a means to

ensure that users are able to see the effect of design on the whole behaviour of the product, be it electromagnetic, thermal, mechanical etc. In this project finite element analysis was carried out using the FEA software ANSYS. The primary unknowns in this structural analysis are displacements and other quantities, such as strains, stresses, and reaction forces, are then derived from the nodal displacements.

V. DESIGN OPTIMIZATION – GENETIC ALGORITHM (GA)

Many methods are used for the design optimization that assumes all the design variables are continuous. But in actual structural optimization almost all the variables are discrete. The GA is a stochastic global search method that mimics the metaphor of natural biological evolution. GA operates on a population of potential solutions applying the principle of survival of the fittest to produce (hopefully) better and better approximations to a solution. At each generation, a new set of approximations is created by the process of selecting individuals according to their level of fitness in the problem domain and breeding them together using operators borrowed from natural genetics. This process leads to the evolution of populations of individuals that are better suited to their environment than the individuals that they were created from, just as in natural adaptation.

b. Advantages of GA

GA's differs from traditional optimization algorithm in many ways. A few are listed here.

- GA does not require a problem specific knowledge to carry out a search. GA uses only the values of the objective function. For instance, calculus based search algorithms use derivative information to carry out a search.
- GA uses a population of points at a time in contrast to the single point approach by the traditional optimization methods. That means at the same time GAs process a number of designs.
- In GA, the design variables are represented as strings of binary variables that correspond to the chromosomes in natural genetics. Thus the search method is naturally applicable for solving discrete and integer programming problems. For continuous variable, the string length can be varied to achieve any desired resolution.
- GAs uses randomized operators in place of the usual deterministic ones. In every generation, a new set of strings is produced by using randomized parents selection and crossover from the old generation.

The objective for the optimum design of the composite drive shaft is the minimization of weight, so the objective function of the problem is given as Weight of the shaft,

$$m = \rho AL$$

$$m = \rho \frac{\pi}{4} d_o{}^2 - d_i{}^2 L$$

VI. RESULTS AND DISCUSSION

A static analysis is used to determine the displacements, stresses, strains and forces in structures or components caused by loads that do not induce significant inertia and damping effects. A static analysis can however include steady inertia loads such as gravity, spinning and time varying loads. In static analysis loading and response conditions are assumed, that is the loads and the structure responses are assumed to vary slowly with respect to time. The kinds of loading that can be applied in static analysis includes, Externally applied forces, moments and pressures Steady state inertial forces such as gravity and spinning Imposed non-zero displacements. If the stress values obtained in this analysis crosses the allowable values it will result in the failure of the structure in the static condition itself. To avoid such a failure, this analysis is necessary. The following figures show the total deformation and shear stresses of various materials.
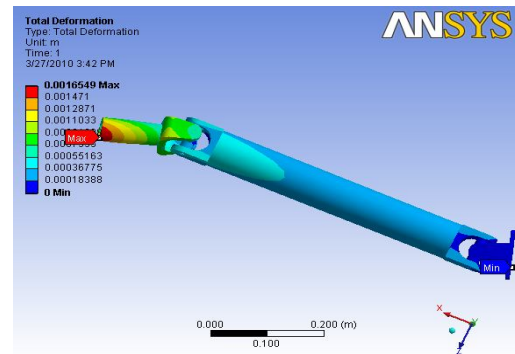

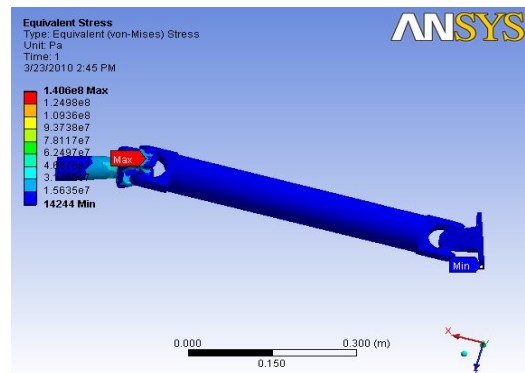Figure 4: Total deformation of E-glass epoxy resin
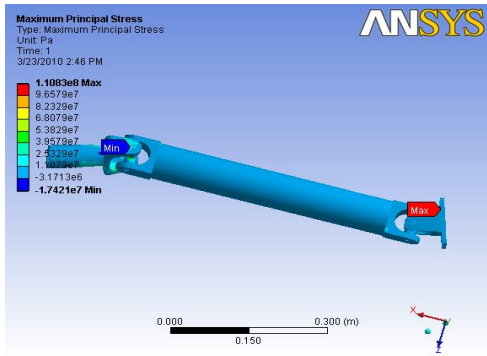

Figure 5: Equivalent stress of E-glass epoxy resin
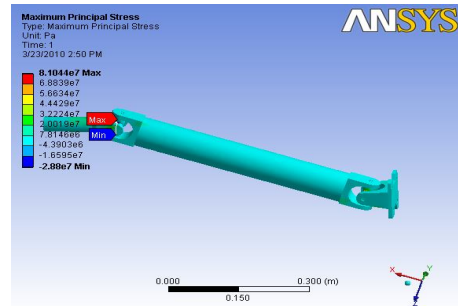
Figure 6: Maximum principal stress of E-glass epoxy resin

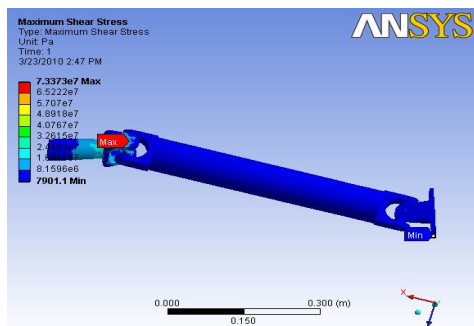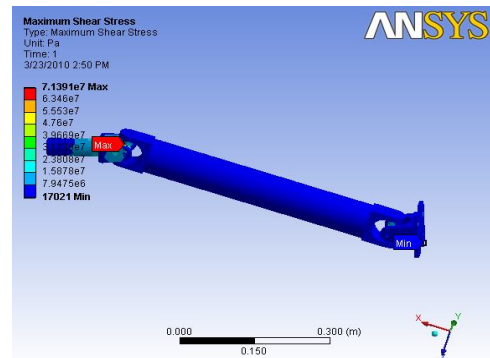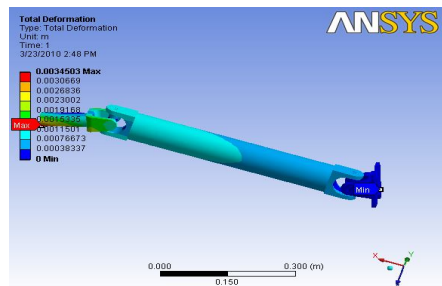

Figure 7: Maximum shear stress of E-glass epoxy resin
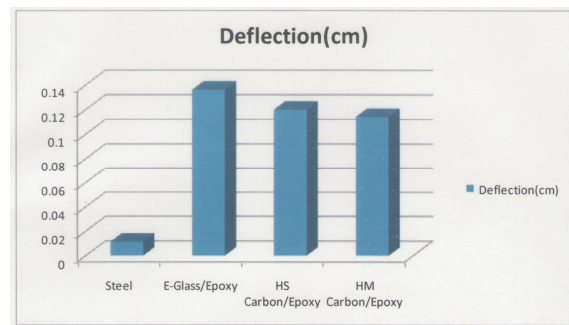

Figure 8: Total deformation of E-glass polyester resin

Figure 9: Equivalent stress of E-glass polyester resin

Figure 10: Maximum principal stress of E-glass polyester resin

Figure 11: Maximum shear stress of E-glass polyester resin
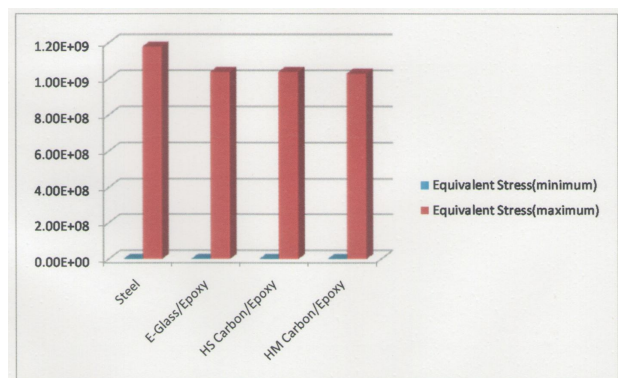

Figure 12: Deflection of drive shafts

Figure 13: Equivalent Stress of drive shafts

Table shows the comparison of Structural Steel, E-glass, E-carbon and E-glass polyresin materials

Property /material	Structural Steel	E-glass	E-carbon	E-glass polyresin
Weight (N)	177.13	46.62	37.3	48.932
%Reduction In Weight	-	73.7 %	78.9%	72.4%
maximum principal stress (pa)	1.28e008	9.74e007	1.11e008	8.1e007
%reduction of maximum principal stress	-	24%	13.3%	36.7%
maximum shear stress (pa)	8.34e007	8.16e007	7.34e007	7.14e007
%Reduction of maximum shear stress	-	2.16 %	11.9%	14.4%

VII. CONCLUSIONS

From preliminary experiments and studies of physical properties like weight, material combination, torque transmitting capacities, etc. it is concluded that:
The analysis results are tabulated as shown above. By the obtained results it can be conclude that the stresses induced in all the materials are within their allowable limits. And it can also be observed that the materials which develop less von-mises stress exhibit a little more deformation. E-glass polyster has 2.5%reduction in Von-Mises stress and 74%reduction in weight than Structural Steel. But it has 20.6% increases in deformation than Structural Steel. By the obtained results it can be conclude that the stresses induced in all the materials are within their allowable limits. And it can also be observed that the materials which develop less von-mises stress exhibit a little more Though E-Glass Polyester Resin induces 18.75% less stresses compared to structural steel, considering the changes in both deformation and stress and density (which is least - 1600 kg/m^3 among all the above materials), it can be concluded that E-Carbon can be used instead of conventional material like structural steel. So that the weight and stresses induced in the drive shaft can be considerably decreased.

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