Design, Failure Analysis and Optimization of a Propeller Shaft for Heavy Duty Vehicle

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Abstract— *The power transmission system is the system which causes movement of vehicles by transferring the torque produced by the engines to the wheels after some modifications. The transfer and modification system of vehicles is called as power transmission system. The power transmission system of vehicles consists of several components which encounter unfortunate failures. Propeller shaft and the universal joints form the important links that help in transmitting power from the engine to the wheels. In this study, analysis is being performed on the universal joint yoke and the propeller shaft. In the universal joint yoke, certain modifications are made in the existing geometry and analyzed for the identical loading and boundary conditions as in the reference paper from which the problem has been taken. It was observed that from the static analysis that the roots of the splines are the areas of high stress concentration. The fatigue analysis revels that the drive shaft fails in the region of high stress concentration as expected.*

In this project the propeller shaft of TATA 1210 was investigated for failures. Considering the system, torque acting on a shaft used to calculate the Stress analysis by using FEA and the results were compared with the calculated values. The stress in the shaft was exceeding the endurance limit causing failure in shaft, the shaft may have failed prematurely due to fatigue loads before the average life of truck. Thus it was important to redesign the shaft so that the induced stress is less than the endurance limit.

Keywords— ***Failure, Analysis, Propeller Shaft, Universal Joint, Stress concentration, Torque.***

I. INTRODUCTION

1.1 Basic concept

A drive shaft, driveshaft, driving shaft, propeller shaft (prop shaft), or Cardan shaft is a mechanical component for transmitting torque and rotation, usually used to connect other components of a drive train that cannot be connected directly because of distance or the need to allow for relative movement between them. As torque carriers, drive shafts are subject to torsion and shear stress, equivalent to the difference between the input torque and the load. They must therefore be strong enough to bear the stress, whilst avoiding too much additional weight as that would in turn increase their inertia. To allow for variations in the alignment and distance between the driving and driven components, drive shafts frequently incorporate one or more universal joints, jaw couplings, or rag joints, and sometimes a splined joint or prismatic joint. The movement of vehicles can be provided by transferring the torque produced by engines to wheels after some modification. The transfer and modification system of vehicles is called as power transmission system and have different constructive features according to the vehicle's driving type which can be front wheel drive.

Most automobiles today use rigid driveshaft to deliver power from a transmission to the wheels. A pair of short flexible driveshaft is commonly used in cars to send power from a differential to the wheels. An automobile may use a longitudinal shaft to deliver power from an engine/transmission to the other end of the vehicle before it goes to the wheels. A pair of short drive shafts is commonly used to send power from a central differential, transmission, or transaxle to the wheels.

1.2 Types of Shaft

Types of Drive Shafts There are different types of drive shafts in Automotive Industry:

- One-piece driveshaft
- Two-piece driveshaft
- Slip in Tube driveshaft

Drive shafts as power transmission tubing are used in many applications, including cooling towers, pumping sets, aerospace, trucks and automobiles. In metallic shaft design, knowing the torque and the allowable shear stress for the material, the size of the shaft's cross section can be determined.

When the length of steel drive shaft is beyond 2000 mm, it is manufactured in two pieces to increase the fundamental natural frequency, which is inversely proportional to the square length and proportional to the square root of specific modulus. Major features of the Drive shaft include its high resistance to dynamic load variations, large deflection angles and uniform load distribution throughout the axial displacement range, low rotational diameter, low weight, and versatile flange connections these features provide an ideal base for standardized drive train design and new power transmission concepts. Heavy Duty Trucks (HDT) need high load carrying capacity. Depending on application of vehicle where the engine and axles are separated from each other, as on four-wheel-drive and rear wheel-drive vehicles, it is the propeller shaft that serves to transmit the drive force generated by the engine to the axles. Sagging causes vibration and results in an increase in noise, to such an extent that the shaft is likely to break when the critical speed is exceeded.

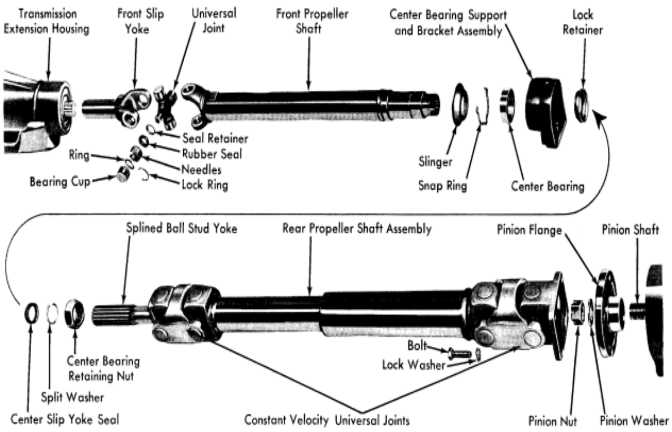

Fig.1.3:Propeller Shaft Detailing

The propeller shaft is naturally designed not to break when used within the service limits expected of use. Defining the length of the propeller shaft is an important task in the production of any vehicle. The power is transmitted from Gearbox to differential by means of propeller shaft. Depending on the length of the vehicle there is a necessity to make the propeller shaft in stages. The orientation of the propeller shaft is a critical factor defining the length of the propeller shaft.

The propeller shaft is a shaft that transmits power from transmission (gear box) to the differential. On one end, propeller shaft in connected to main transmission shaft by universal joint. On the other hand, it is connected to differential pinion shaft by another universal joint. Propeller shaft transmits the rotary motion of main transmission shaft (coming from gear box) to the differential so that rear wheels can be rotated. A sliding (slip) joint, is also fitted between universal joint and propeller shaft on transmission side which takes care of axial motion of propeller shaft. Propeller shaft is made of a steel tube which can withstand torsional stresses and vibrations at high speeds. It is important to note that the differential pinion shaft and transmission main shaft are not in single horizontal level. The rear axle and differential is attached to automobile frame via springs. Therefore, distance between differential and gear box keeps on changing as vehicle moves along irregular road surface. Angle of propeller shaft also changes due to this fact. Universal joints provided at two ends takes care of these two changes. The propeller shaft along with universal joints.

An automotive drive shaft transmits power from the engine to the differential gear of a rear wheel drive vehicle. The drive shaft is 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 which increases the total weight of an automotive vehicle and decreases fuel efficiency. So, a single piece drive shaft is preferred here and the material of it is considered to be Titanium alloy because of its high strength and low density. Drive shafts are carriers of torque and are subject to torsion and shear stress, equivalent to the difference between the input torque and the load. They must therefore be strong enough to bear the stress, whilst avoiding too much additional weight as that would in turn increase their inertia

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1.3 Universal Joint

An automotive drivetrain is an assembly of one or more driveshaft, universal joint, and slip joint that forms the connection between the transmission and the drive axle. The function of drivetrain is that it allows the driver to control the power flow, speed and multiple the engine's torque.

A universal joint (U-joint) is a joint in a rigid rod that permits the rod to move up and down while spinning in order to transmit power by changing the angle between the transmission output shaft and the driveshaft as shown in Figure1. The most common types of U-joint used in automotive industry is Hooke or Cardan joint (Birch and Rockwood, 2005). A basic U-joint consists of driving yoke, driven yoke, spider and trunnions. Each connection part of the spider and trunnion are assembled in needle bearing together with the two yokes. The driving yoke force the spider to rotate the other two trunnions. The previous action causes the driven yoke to rotate.

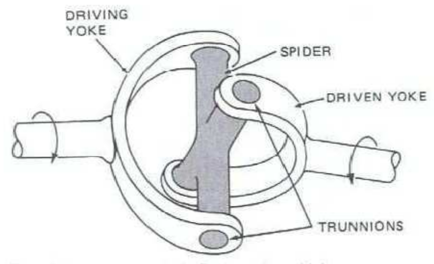

Fig 1.1:Universal coupling.

A universal joint is used where two shafts are connected at an angle to transmit torque. In the transmission system of a motor vehicle, the transmission main shaft, propeller shaft and the differential pinion shaft are not in one line, and hence the connection between them is made by the universal coupling.

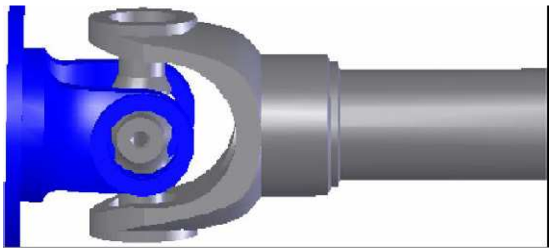

Fig 1.1:Connected to the differential gear box

One universal joint is used to connect the transmission main shaft and the propeller shaft, other universal joint is used to connect the other end of the propeller shaft and the differential pinion shaft. A simple universal joint consists of two Y shaped yokes, one on the driving shaft and other on the driven shaft and the cross piece called the Spider.

There are two types of U-joints, the cross and roller type and the ball and trunnion type. The cross and roller type is used the most; it allows the drive shaft to bend. The ball and trunnion type less frequently used; it allows the drive shaft to bend and also permits backward and forward motion of the drive shaft.

II. CAUSES OF SHAFT FAILURE

Failure analysis is the process of collecting and analyzing data to determine the cause of a failure and how to prevent it from recurring. Failure analysis and prevention are important functions to all of the engineering disciplines. A component or product fails in service or if failure occurs in manufacturing or during production processing. In any case, one must determine the cause of failure to prevent future occurrence, and/or to improve the performance of the device, component or structure. It is possible for fracture to be a result of multiple failure mechanisms or root causes. A failure analysis can provide the information to identify the appropriate root cause of the failure.

2.1 The common causes of service failure are:

Misuse or Abuse.

- Road condition.
- Environment condition.
- Improper maintenance.
- Improper material.
- Poor storage condition

It was observed from the research papers that the failure took place at the areas of high stress concentration. The fatigue Analysis revels that the drive shaft fails in the region of high stress concentration as expected.

III. PROBLEM IDENTIFICATION

3.1 Basic Problem

To identify the main cause of failure in the Propeller shaft. Study the common causes of service failure. Investigate the loading condition of a Propeller shaft. Since we have collected all the data of existing Propeller shaft from TATA truck 1210 model so we could find out the area or component which is turned into failure.

3.2 Failure Analysis

Literature review for fatigue failure analysis is carried out by referring journals, books, manuals, technical papers and related documents. Considering the areas where the stress concentration is high, as per the literature review and research the Universal Coupling area is affected more and it turned to failure.

It was observed that from the static analysis that the roots of the splines are the areas of high stress concentration. The fatigue analysis revels that the drive shaft fails in the region of high stress concentration as expected.

3.3 Stress Concentration Factor

An experimental and finite-element analysis of universal coupling was carried out with help of ANSYS for existing torque condition. In this work finite element analysis of a Propeller shaft had been taken as a case study. The maximum stress point and dangerous areas were found by the deformation analysis of Propeller shaft. Structural analysis was carried out on the FE model of drive shaft, and potential areas of high stress concentration are obtained.

3.4 Life of Propeller Shaft

The transmission system of a truck is totally depend on the working of its Propeller shaft. By figuring out the failure of Shaft we can increase the Life of a Propeller Shaft

3.5 Weight of Shaft

As we know that the heavy weight machine or component is a big thread to the automobile Industries, there is almost a direct proportionality between the weight of a vehicle and its fuel consumption. In this research we tried to reduce the weight of Propeller shaft.

Fig.3.1: Universal coupling failure.

(The typical failure that occurs at the coupling location after approximately 7 to 9 years of service life.).

IV. PROBLEM FORMULATION

4.1 Investigate stress

Propeller shafts in commercial heavy duty vehicle are subjected to cyclic loads due to variation in the torque demanded by the varying road loads. The objective of this Project is to identify the root cause of failure in propeller shaft.

4.2 Predict Shaft Failure

Drive shafts are one of the most important components in vehicles. It generally subjected to torsional Stress and bending stress due to weights of components. Thus, these rotating components are susceptible to fatigue by the nature of their operation. The failure Analysis of a Propeller shaft is performed in ANSYS software.

4.3 Design of Propeller Shaft

We have gathered all the data of Propeller shaft from the workshop. We are using the Propeller shaft of TATA truck model no. 1210 and as per our project research is concerned we analyze the failure and implement the modification to the existing Propeller shaft.

4.4 Stress Concentration Factor

In this project an attempt has been made on prediction of fatigue life of the drive shaft using FEA technique. Structural analysis was carried out on the FE model of drive shaft, and potential areas of high stress concentration are obtained. Von Mises stress, fatigue damage, fatigue life, factor of safety and total deformation are the results of fatigue analysis.

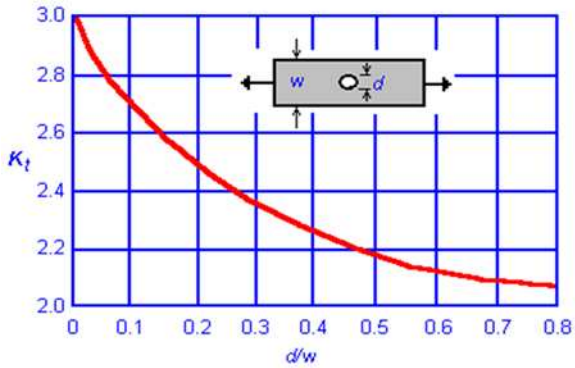

Fig.4.1:Stress Concentration curve

With Stress concentration factor, the value of endurance stress reduces significantly

d/w=28mm/70mm

=0.4

Kt=2.3 (existing shaft's dimension).

4.5 Weight Optimization

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, if it can be achieved without increase in cost and decrease in quality and reliability. By modifying the existing shaft model we can literally reduce the Weight in consideration to Strength of Shaft.

4.6 Increase life of the Propeller shaft.

Since we have collected the information from where the shaft failure has occurred. By modifying the existing propeller shaft as per the given constrain we can increase the life of a Shaft.

Literature review for fatigue failure analysis is carried out by referring journals, books, manuals, technical papers and related documents. Considering the areas where the stress concentration is high, as per the literature review and research the Universal Coupling area is affected more and it turned to failure. By modifying the existing shaft dimensions we could increase strength and life of the Shaft.

Predicting the fatigue life of Propeller Shaft of a heavy duty truck from a duty cycle calculated as if a truck running 8 hours/day i.e. 330days/year. We have assumed that the life of a truck is 15 years. Thus, the truck runs 8hrsx 330days per year i.e. 2640hrs/year.

Now for 15 years 2640hrs x 15yrs = 39,600 hours. i.e. 23, 76,000 Min.

As we found out the total minutes the truck running on max torque is approximately 0.5% of the total minutes i.e. 11880 min. Thus total load cycle on

Max. Torque is 11880x 1800 rpm = 21384000 cycles i.e. 2.17.

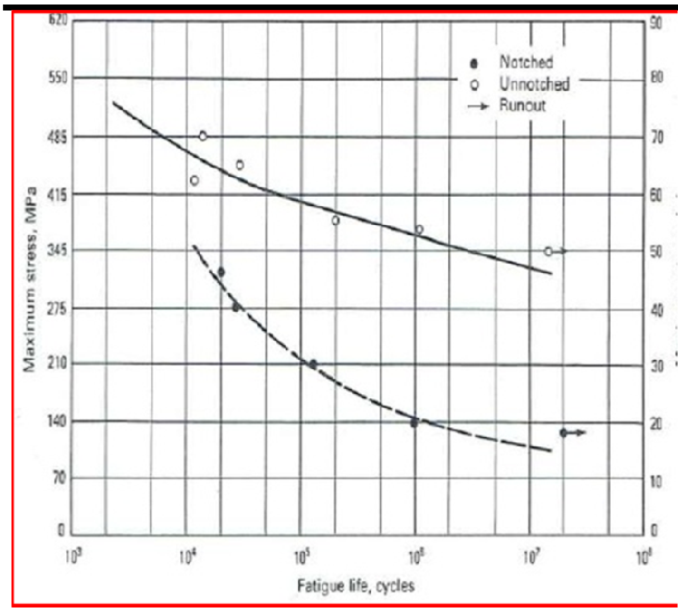

Fig.4.2:S-N Curve

V. RESEARCH METHEDOLOGY

5.1. Data Acquisition

5.1.1. Propeller Shaft Specification

Table5.1.1

Truck Model number TATA 1210	
Outer diameter of shaft, Do	90 mm
Inner diameter of shaft, di	72 mm
Length of the Shaft, L	2100 mm
Torque max, T	625 Nm
Speed max, N	1800rpm

5.1.2. Material Properties of AISI 1045 (SM45)

Table 5.1.2

Young's modulus	E	Gpa	206
Shear Modulus	G	Gpa	80
Poisson's ratio	V	-----	0.29
Density	ϱ	Kg/m^3	7850
Yield strength	Syt	Mpa	530
Ultimate strength	Sut	Mpa	625

5.1.3. Chemical composition

Table 5.1.3

Carbon	0.15-0.25%
Silicon	0.10-0.35%
Manganese	1.30-1.70%
Sulphur	0.060 Max
Phosphorus	0.060 Max
Chromium	0.25% Max
Nickel	0.40% Max

5.2 FE Model of Shaft

Fig.5.1: FE Model of Assembly

5.2.1 Boundary Condition

Fig.5.2: Torque of 625N.m applied at one end.

FEA Results

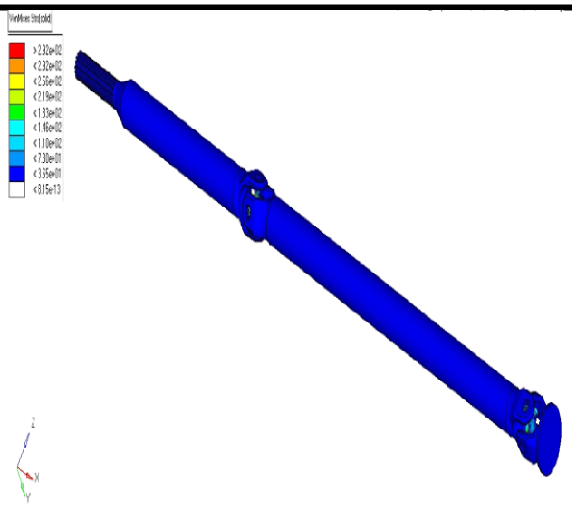

Fig.5.3:Maximum Von Misses stresses induced on the shaft is (Max-292Mpa)

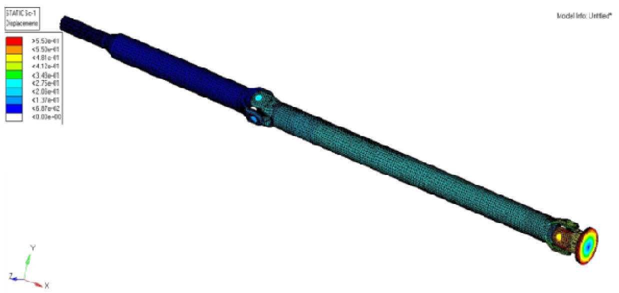

Fig.5.4: Displacement of shaft (0.6mm)

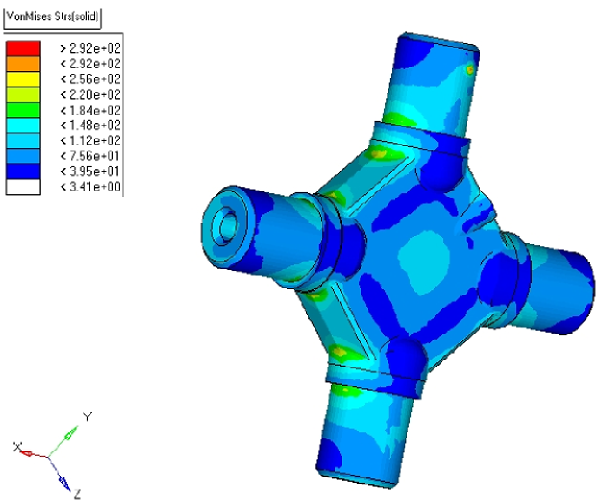

Fig.5.5: maximum Von Misses stresses induced on the spider (Max-292Mpa).

5.2.2 Modification to improve the Life of Coupling beyond Truck average life of 15years

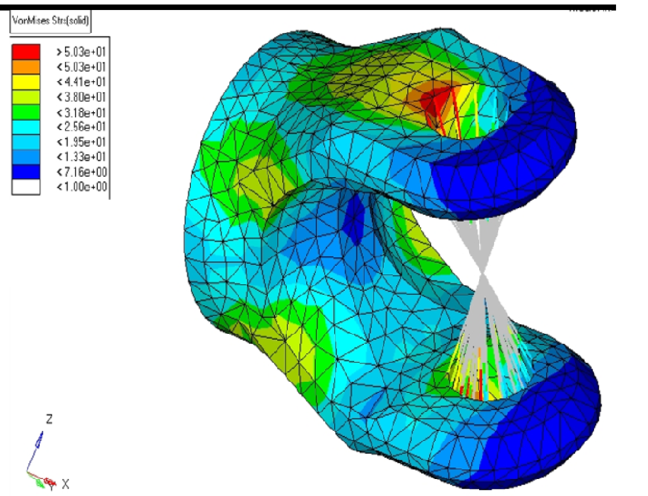

Fig.5.6: Modified Coupling

Fig. 5.6 shows the maximum stress induced 53Mpa, by 2.5% increase in dimensions, thus it is less than the material fatigue strength beyond the truck life of 2.1e7 cycles. Thus finalizing the 2.5% increase in overall coupling dimensions.

5.2.3 Universal Joint

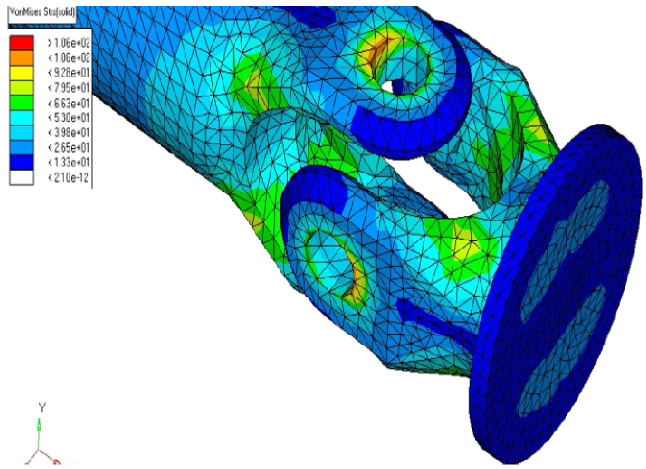

Fig.5.7: Modified Universal Joint

Fig. 5.7 shows that, if the induced stress value is 106Mpa, the coupling is expected to fail after 1e7 cycle which is approximately 7 to 9 years of service life. Refer S-N curve

5.2.4 Shaft Modification according to Universal Coupling

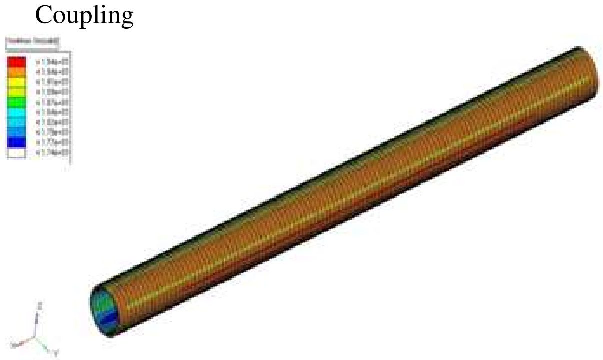

Fig.5.8: Modified Shaft

Fig. 5.8 shows the dimension of hollow shaft has been updated from OD 90mm and ID mm to OD 92.5mm ID 82mm (thickness=5.25), these are the final optimized dimensions for shaft as the thickness cannot be reduce below 5mm as it will cause geometric instability in torsion

5.3 Design Calculation

a) Design torque:

$Ta = \frac{60 \times P \times K1}{2 \times \pi \times N}$

Where K_1= Load factor

Td = 625Nm. (Given)

P = 67319.84W.

b) **Maximum shear stress:**

$\tau_{max} = Tr/J$

Where,

T = Torque

r = outer radius

J = polar moment of inertia

$J = \pi\,(Do^4 - Di^4) / 32$

$= 274.862 m^4$

T = 625 Nm.

R = 46.25 (Do=92.5)

Therefore **τmax = 105.1Mpa**

c) **Torsional deflection of shaft:**

θ = LT / JG

Where,

θ = angular shaft deflection

L = length of shaft

T = torque

J = Polar moment of inertia.

G = modulus of rigidity

L = 2100mm, T = 625 Nm

$J = 274.862 m^4$

Therefore **θ = 5.96^{o}**

d) **Combined twisting moment and bending moment on shaft:**

$\tau_{max} = \frac{1}{2}\sqrt{\sigma b^2 + 4\ \tau^2}$

Where,

σb = bending stress (since $\sigma b = \frac{ult.\ strenght}{factor\ of\ safety}$)

τ = Shear stress

Factor of safety = 2

τ_{max}= 188.30 Mpa

e) **Mass of the shaft**

$M = \varrho AL = \varrho\,\pi (Do^2 - Di^2) \times L/4$

Where,

ϱ = density of material

Do = Outer diameter of shaft.

Di = Inner diameter of shaft.

L =Length of the shaft

Therefore the weight of Existing Shaft = **37.75 kg.**

Since $\varrho = 7850\ kg/m^3$

Do = 90 mm

Di = 72 mm

L = 2100 mm

f) **Mass of the Shaft for Optimized Model**

Therefore the weight of optimized Shaft = **23.72 kg.**

MODEL	WEIGHT in kg
EXISTING	37.75
MODIFIED	23.72
FINAL OPTIMIZED	14.03

VI. RESULT

We have compared the maximum stress of the Propeller Shaft with FEA software, Research Papers, S-N curve and from Calculations. We find out that the max. Stress which causes failure in Shaft is 110 Mpa for 107 no. of cycles. So if we reduced the Stress in the affected area of the Shaft we probably improve the life of Propeller Shaft. The calculated max. Shear stress is 105.1 Mpa.
Since modifying the design of shaft by change in the dimension, thus providing the suitable thickness to the Propeller Shaft which causes the weight reduction and by which the cost also get reduced

VII. DISCUSSION AND CONCLUSION

By analyzing the existing Propeller Shaft in the FEA software we have found the Torsional stress, bending stress, shear stress etc. By taking these results into consideration we have compared it with the Modified design. As we know the failure of the Propeller shaft is caused by the stress concentration factor i.e. the stress is concentrated at the one point and thus it lead to the fatigue life of the material. We have modified the Universal Coupling which is the stress concentrated area to improve the life of the Propeller Shaft. We have compare the maximum stress of the Propeller Shaft with FEA software, Research Papers, S-N curve and from Calculations. We find out that the max. Stress which causes failure in Shaft is 110 MPa for 107 no. of cycles. So if we reduced the Stress in the affected area of the Shaft we probably improve the life of the Propeller Shaft.
Drive shafts are one of the most important components in vehicles. It generally subjected to torsional Stress and

bending stress due to weights of components. Most of the time these components are victim to fatigue by the nature of their operation. The total deformation of the drive shaft is 0.6 mm. The factor of safety for the drive shaft is more than 1.

Hence, the drive shaft is safe. The life of the drive shaft is different for different duty cycle. Over all the cause for fatigue failure of the drive shaft is due to overloading and Stress concentrated area. By reducing the Stress in the affected area of the Shaft we probably improve the life of Propeller Shaft. The calculated max. Shear stress is 105.1 MPa. Now the no. of cycle is increased to much more than 107 and thus increase the life of the truck to more than its average life.

VIII. FUTURE SCOPE

The Propeller Shaft of TATA truck 1210 is used for failure Analysis, by modifying the Shaft from its original design to the optimized design it's clearly improve the life of the shaft i.e. Increase beyond the average life of the truck which is the great achievement related to my Project research.

Because of this human life can be in great danger if we don't know when, where and how the Propeller Shaft will failed. It is very important to know the accurate prediction for the drive shaft to fail. It will nearly help the automobile industries particularly for shafts assembling. Our research shows that how we reduced the induced stress in the shaft to improve it from fatigue failure.

The cause of failure and predicting the fatigue life to prevent future occurrence and to improve the performance of the device, component or structure has been achieved. It will help the manufacturer to improve the performance

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