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Effect of Keyways in the Design of Drive Shaft: A Case Study

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ABSTRACT

The discontinuity in shaft arises due to the presence of keyway, groove, crack, etc. The objective of present work is to study the deformation, equivalent stresses and maximum shear stresses generated in the circular solid shaft and hollow shaft in the presence of keyways (rectangular, square and tapered), keeping the volume of material constant. The effects of different shaped keyways present in the solid shaft are studied as regards to their deformation, equivalent stresses and maximum shear stresses under the action of applied torque. The 3D modeling and analysis of drive shaft with and without keyway is carried out using ANSYS software. It is concluded that rectangular keyway is best from the design point of view of solid shafts.

Keywords: Torque, Moment, Keyway, Finite Element Analysis, Keyway.

I INTRODUCTION

Drive shaft is generally used in automobiles for the transfer of rotary motion and torque to the differential using helical gear box which results motion of the rear wheels. Fig. 1 shows the application of drive shaft in automobiles. The wide applications of drive shaft, consisting of structural steel, reflect in automobile world like, buses, trucks, aero planes, etc. [9]. Failures of shafts not only result in replacement cost, but also in process downtime. This could have a drastic effect on the productivity and, more importantly, late delivery. It had been found that the downtime was 3 days, and 1,800 metric tons of steels were lost before the failed shaft could be replaced [7].

The failure of drive shaft may result from many reasons including improper designs, manufacturing errors or improper applications. Design errors include selection of poor quality or wrong materials, improper gear geometry, inappropriate lubrication system, etc. whereas improper mounting and installation, inadequate lubrication, poor cooling, and poor maintenance lead to application errors. Manufacturing errors could be poor machining or inaccurate heat treatments of drive shafts leading to poor mechanical properties [13].The shaft may fail due to the discontinuity present in the shaft such as keyway. They are generally used to connect shaft with hubs. These are available in several shapes such as rectangular, square, tapered, woodruff, etc. and its design is fully controlled by the standards based on only one parameter, the shaft diameter [2].

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The inclusion of keyways in the drive shaft leads to complex cross-section leading to stress concentrations at the sharp corners. The effect of mechanical loading on complex cross-section can be more accurately analyzed using Finite Element Analysis (FEA). FEA is a method of solving, usually approximately, certain problems in engineering and science which does not provide exact solution. The method is applied if either shape or loading on the component is complex. The method is applied to the problems involving a wide range of phenomena, including vibrations, heat conduction, fluid mechanics and electrostatics, and a wide range of material properties, such as linear-elastic behaviour and behaviour involving deviation from Hooke's law [6].

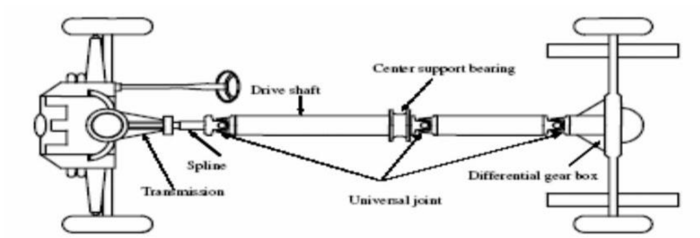

Figure 1: Application of drive shaft in automobiles [11]

In the present work, solid and hollow drive shafts incorporating different types of keyways is analyzed using FEA and deformation, equivalent stresses, maximum shear stresses are calculated at critical locations keeping volume of solid and hollow shaft constant. The results are compared for solid and hollow shaft considering keyways of different shapes.

II ANALYSIS OF DRIVE SHAFT

The circular solid and hollow drive shaft with and without keyways (rectangular, square and tapered) is modeled and analyzed in ANSYS software and deformation, equivalent stress and shear stress distributions in drive shafts are investigated as a case study for the following material properties [12]:

The density of material (structural steel): Poisson's ratio: 0.3, Young modulus: 207 GPa and shear modulus: 80GPa.

The shaft analysis is carried out under the following assumptions [4, 8]:

- It rotates at a constant speed.
- The shaft has a uniform circular cross section.
- The stress-strain relationship for steel material is linear and elastic.
- All damping and non linear effects are excluded.

Maximum shear stresses

For solid shaft,

$$Maximum\ shear\ stress, \tau = \frac{16 \times T}{\pi \times D_s^3} \qquad (1)$$

For Hollow Shaft,

$$Maximum\ shear\ stress, \tau = \frac{16 \times T \times D}{\pi \times (D^4 - d^4)} \quad (2)$$

Where, T = torque on the shaft, D_s = Diameter of solid shaft

D = Outer diameter of hollow shaft, d = Inner diameter of hollow shaft

Equivalent stresses

$$\text{Equivalent stress (Von Mises stress)}, \sigma_{eq} = \sqrt{(3\tau^2)} \quad (3)$$

Angle of rotation of shaft

$$Angle\ of\ rotation, \theta = \frac{T \times L}{I_p \times G} \quad (4)$$

Where, L = Length of shaft, I_p = Polar moment of inertia

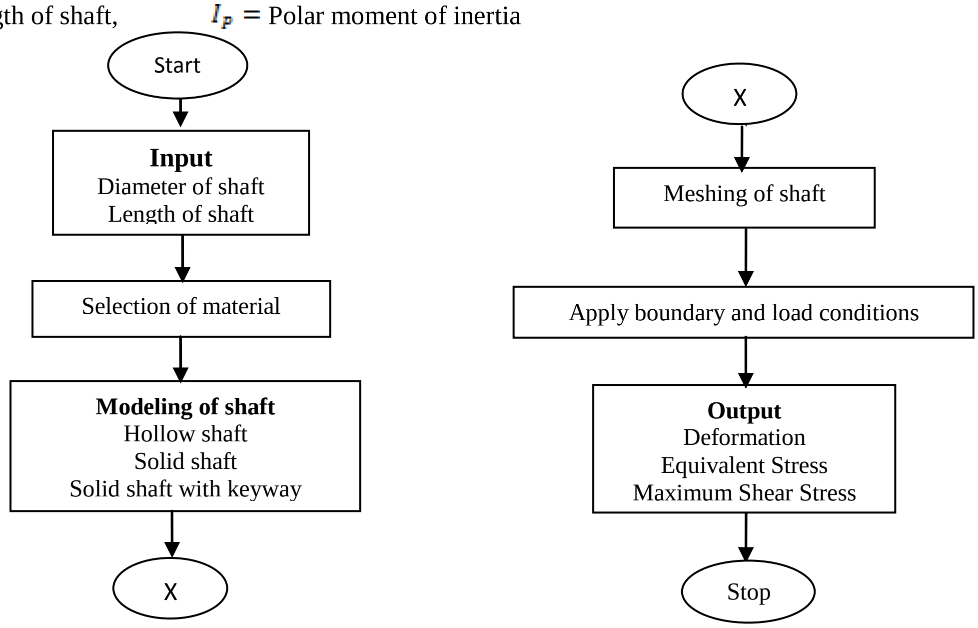

Figure 2: Flowchart for calculation of deformation and stresses in drive shaft

The 3D modeling of solid and hollow shaft and FEA is carried out in ANSYS 16.2 for the following dimensions:

Outer diameter, D= 80 mm, Inner diameter, d = 50 mm, Length, L=1000 mm [12]. The diameter of solid shaft is determined by equating it's volume to volume of hollow shaft. Thus, diameter of solid shaft = 62.5 mm. The rectangular keyway dimensions are [5]: width =18 mm, depth = 7 mm and length = 140 mm.

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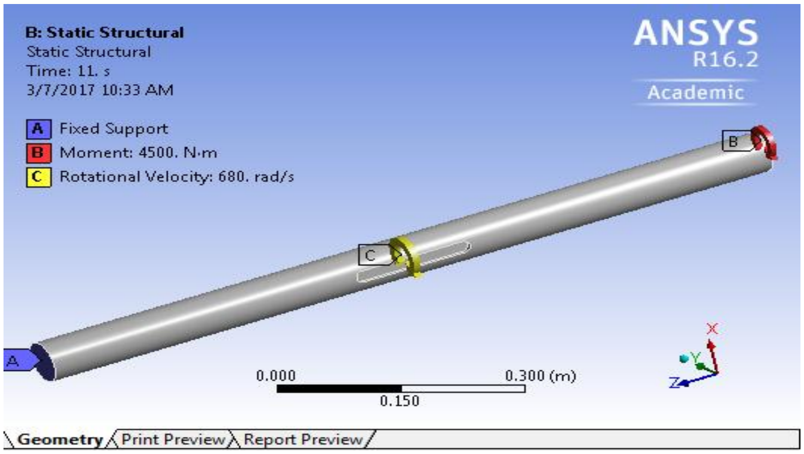

Figure3: Load and boundary conditions of solid shaft with rectangular keyway

After modeling, the mesh is generated using tetrahedron with element size of 4 mm, no. of nodes 265668 and no. of elements 76762. The hexahedral element consists of 20-nodes with three degrees of freedom at each node capable of translation in x, y and z nodal direction. Fig. 3 shows load and boundary conditions of solid shaft having rectangular keyways. One end of the shaft is fixed and torque (3500 N-m - 4500 N-m) is applied at the free end [12].Similar boundary conditions are used for hollow/solid shafts with/without keyways.

III RESULTS AND DISCUSSION

Figs.4&5 shows equivalent stresses and maximum shear stresses induced in the solid shaft with rectangular keyways. Fig. 4 shows the equivalent stresses in the solid shaft with rectangular keyway with minimum at the centre and maximum at the edge of rectangular keyway. Fig. 5 shows the maximum shear stress in the solid shaft with keyway with minimum at the centre and maximum at the edge of keyway.

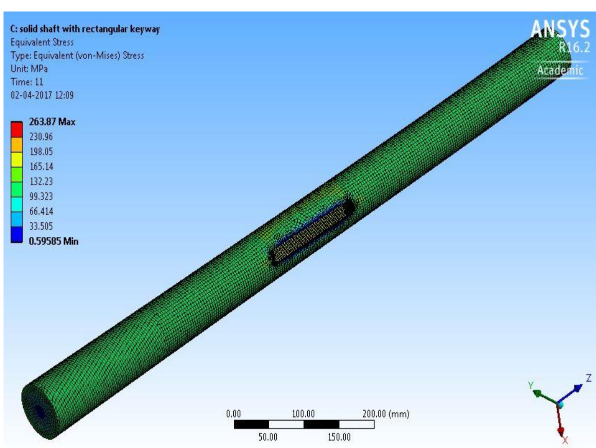

Figure 4: Equivalent stress in solid shaft with rectangular keyway

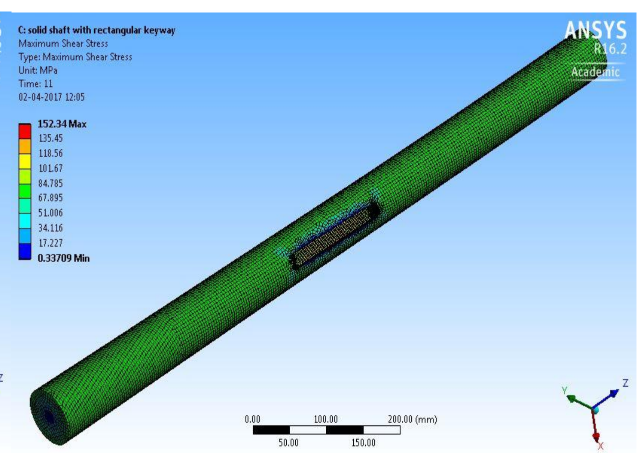

Figure 5: Maximum shear stress of the solid shaft with keyway

Fig. 6 shows the variation of deformation with torque applied for different types of shaft. As expected, the deformation increases with increase in torque value; however, it is less in solid shaft as compared to the hollow shaft. Discontinuity (keyway) in solid shafts increases the deformation in the order: tapered > square > rectangular.

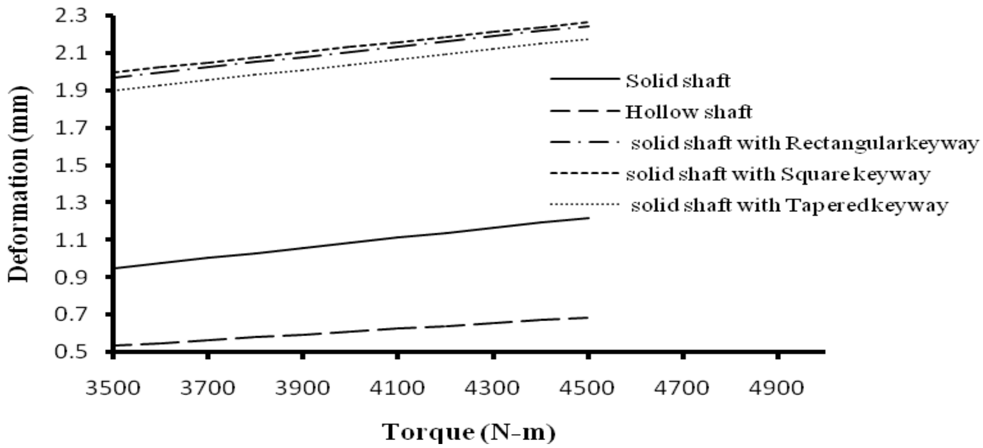

Figure 6: Effect of torque on deformation for different types of shaft

Fig. 7 shows the variation of equivalent stresses generated in different types of shaft. As expected, the equivalent stresses increases with an increase in torque applied. The stresses in hollow shaft are less as compare to solid shaft. Discontinuity (keyway) present in the shaft increases the equivalent stresses. The equivalent stresses in solid shaft with rectangular keyway are minimum as compared to the square/tapered keyways.

Fig. 8 shows the variation of maximum shear stresses generated with torque in different types of shaft. As expected, the maximum shear stresses increases as torque increase. The stresses in hollow shaft are less as compared to the solid shaft and discontinuity (keyway) in the shaft increases the maximum shear stresses. The stresses with rectangular keyway are minimum as compared to the other keyways.

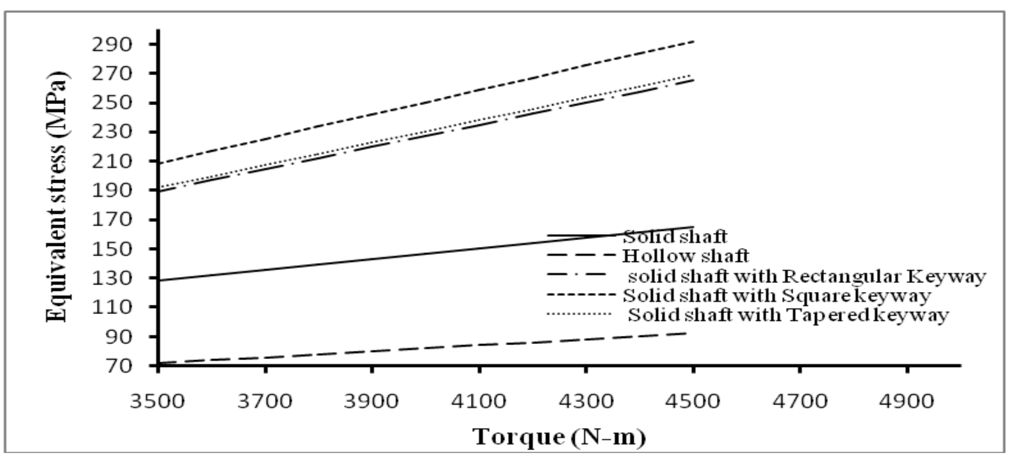

Figure 7: Effect of torque on equivalent stresses generated in different shaft with and without keyways

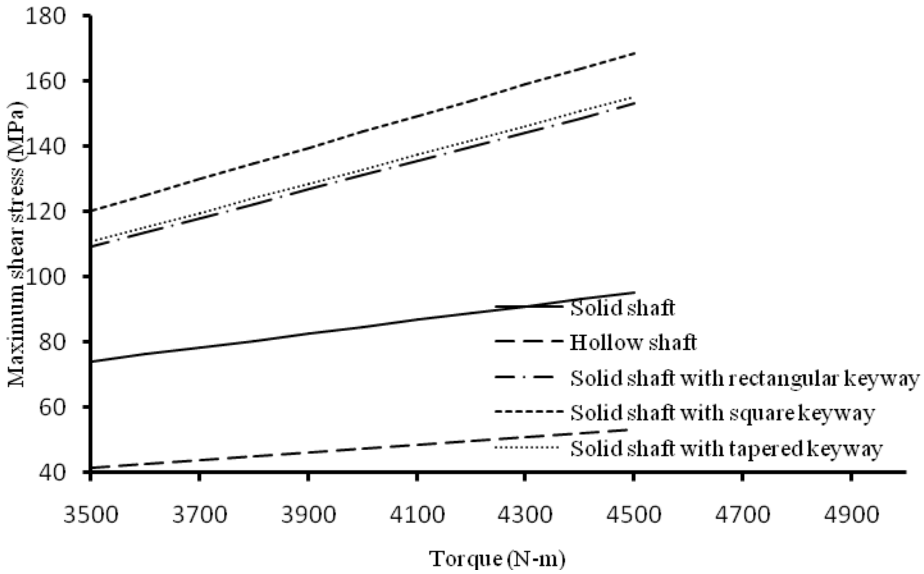

Figure 8: Effect of torque on maximum shear stress generated in different shaft with and without keyways

Table 1 shows comparison between the solid and hollow shafts as regards to the deformation, equivalent stresses and maximum shear stresses at 4500 N-m torque. Table 2 shows the deformation, equivalent stresses and maximum shear stresses in solid shafts with different shapes of keyways such as rectangular, square and taper at 4500 N-m torque. It is concluded that rectangular keyway is best from the design point of view of solid shafts.

Table 1: Deformation, Equivalent stresses and Maximum shear stresses in solid and hollow shafts

Parameters	Solid shaft	Hollow shaft
Deformation, mm	1.22	0.6868
Equivalent stresses, MPa	165.1	92.34
Maximum shear stresses, MPa	95.319	53.307

Table 2: Deformation, Equivalent stresses and Maximum shear stresses generated in solid shafts with different shapes of keyways

Parameters	Solid Shaft with rectangular keyway	Solid shaft with square keyway	Solid shaft with tapered keyway
Deformation, mm	2.25	2.26	2.17
Equivalent stress, MPa	265.13	292.08	268.8
Maximum shear stress, MPa	153.05	168.62	155.18

IV CONCLUSIONS

The design and analysis of hollow and solid drive shafts with/without keyways is carried out in ANSYS software. For given dimensions of the shaft, the following conclusions are drawn from the total deformation, equivalent stresses and shear stresses distribution in the shaft:

1) The total deformation in hollow shaft is less as compared to the solid shaft in the absence of keyway. However, the deformation in solid shaft with keyways is more as compared to the solid shaft. Discontinuity (keyway) in solid shafts increases the deformation in the order: square > tapered > rectangular.
2) The equivalent stresses in shafts are maximum at the outer surface and minimum at the inner surface. The equivalent stresses in hollow shaft are approximately 44% less as compared to the solid shaft, if volume remains same. The equivalent stresses are least in solid shaft the presence of rectangular keyway.
3) The maximum shear stress is maximum at the outer surface and minimum at the inner surface. The maximum shear stress in hollow shaft is approximately 44% less as compared to the solid shaft, if volume remains same. The maximum shear stress is least in solid shaft in the presence of rectangular keyway.

   It is concluded that rectangular keyway in solid shaft is best as far as the total deformation, equivalent stresses and shear stresses generated is concerned.

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