International Journal of Mechanical and Aeronautical Engineering Vol.1, No. 1,September, 2017
© (2017) APISE Press, Hong Kong

Effect of Transverse Eccentric Ballistic Damage on Static Torsional Strength of Tail Drive Shaft of Helicopter

Qasim Zaheer [1,a*], Abdullah Ehtisham [1,b] and Aun Haider [1,c]

[1] Department of Aerospace Engineering, CAE, NUST, Risalpur, Pakistan

Abstract. Military helicopters have high probability of acquiring ballistic damage during their operations. One such damage concerned with the drive train of tail rotors of helicopter is due to ballistic effects that may be introduced because of passage of bullets or other ballistic objects. The ballistic damage may jeopardize the structural integrity of the shaft. The focus of the work exhibited here is to analyze the effect of transversely varying ballistic impact location on the static torsional strength of tail rotor drive shaft. The holes generated as a consequence of ballistic impact turned out to be the areas of stress concentration which is rational. The maximum torsional shear stress was calculated for each case and comparison was drawn with yield strength and ultimate strength using failure theories assorting the drive shaft as safe or unsafe. Moreover, the effect of varying ballistic location on the magnitude of maximum torsional stress is also discussed.

Keywords: *Ballistic Damage; Torsional Strength; Tail Drive Shaft*

I. Introduction

Helicopters make use of tail rotors to efficiently counter act the inertia generated by the main rotor assembly. The tail rotors not only produce the resistive effect but also provide directional stability and control. The power plant of the helicopter supplies power to the main rotor as well as to the tail rotor. Depending upon the power consumption and hence the torque produced by main rotors of helicopter, the tail rotor in response to the main rotors, generates the required thrust for direction stability by changing the pitch of rotor blades. The requirement of thrust produced by the tail rotors vary with respect to the flight operation at hand, may it be hover, forward flight, climb or descent. Consequently, the power or torque requirement of tail rotor to produce the required thrust also changes. The tail rotor receives the requisite power by means of a power train that consists of a single/series of shafts that translate the drive from the engine to the tail rotor. Any damage suffered by this shaft may render the helicopter uncontrollable and loose directional stability as well. So, the determination of the effect of this damage on the strength and stiffness of the shaft holds paramount importance.

Manuscript received May 1, 2017; revised June 1, 2017; accepted July 30, 2017.

*Email: qasimzaheer1985@gmail.com

II. Literature Review

A study was carried out to ascertain the causes of tail rotor failures. The percentage of various causes of tail rotor failures is depicted in Figure 1. The study revealed that the largest amount of tail rotor failures is due to the damage sustained by the tail drive shaft. A helicopter performing normal operation has a 30% chance of getting struck by external objects [1]. This percentage increases substantially for a rotorcraft performing mission in battle zones and forward operational bases. Hence, damage analysis of tail drive shaft has become critical as the results help in establishing information regarding integrity of a damaged shaft.

In literature, the torsional strength of damaged aluminum tail drive shaft under defined loading conditions was analyzed and same analysis was repeated using composite tail drive shaft. It was concluded that composite shafts possess the required torsional strength and hence can be used instead of aluminum shafts as they provide added advantage of weight reduction [2]. A similar conclusion was also drawn by comparing the torsional analysis of carbon epoxy tail drive shafts and the steel shafts [3]. Another study revealed that

© (2017) APISE Press, Hong Kong

tail drive shaft, upon sustaining relatively large ballistic damage, would yield severely around the damaged area under operational conditions. The experimental and Finite Element Analysis revealed that the shaft would not fail catastrophically as the measured static strength of damaged was greater than design limit load. The proposed repair scheme restored static strength however, the dynamic performance of tail drive shaft was restricted to few flight hours [6].

The damage sustained by the tail drive shaft of helicopter depends upon the ballistic trajectory and impact location, subsequently the torsional strength of damaged drive shaft varies. The variation of ballistic damage at different locations along the longitudinal centerline of tail drive shaft was studied previously by Hemanth Kumar C and Swamy [2] and it was revealed that the holes have no impact on the structural integrity of the damaged shaft and hence the helicopter can land safely. In this paper, the effect of transverse eccentric ballistic damage on torsional strength of tail drive shaft of helicopter is studied.

III. Methodology

The conventional Finite Element Analysis of the undamaged and damaged tail drive shaft subjected to the torsional load is carried out using ANSYS APDL®. The material used for the subject tail drive shaft is extracted from literature [2]. Moreover, the dimensions of tail drive shaft are also kept the same. Material properties of aluminum alloy tube 2618A (AIR 9094) T851 used for the tail drive shaft is given in Table 1.

Table 1 : Material Properties of Aluminum Al. tube (AIR 9049) T851

MATERIAL PROPERTIES	NUMERICAL VALUES
Tensile Yield Strength	340 N/mm^2
Tensile Ultimate Strength	420 N/mm^2
Ultimate Shear Stress	254 N/mm^2
Young's Modulus	74000 N/mm^2
Poisson Ratio	0.33
Modulus of Rigidity, G	28462 N/mm^2

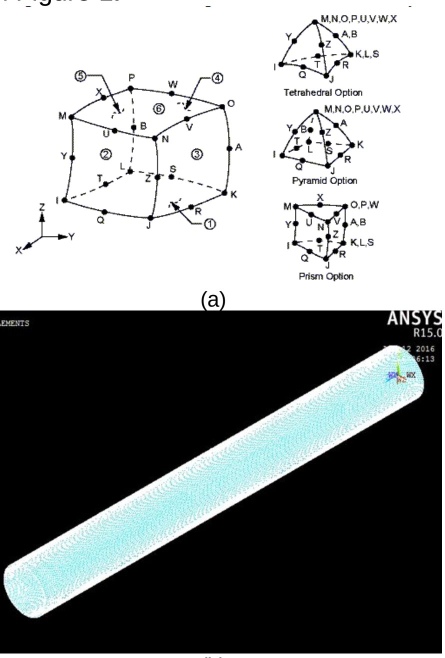
The complete tail drive shaft inside the tail boom is composed of five shafts connected to each other. For analysis purpose, the dimensions of single shaft are considered and the torsional load in terms of torque is applied at one end. Incorporating a factor of safety in the loading conditions used in the previous analysis of same shaft [2], the maximum torsional load along with the geometrical dimensions of subject shaft is given in the Table 2.

Table 1 : Dimensions and the loading conditions of Tail Drive Shaft

DIMENSIONS	VALUES
Outer diameter, do	63 mm
Inside diameter, di	59.8 mm
Wall thickness, t	1.6 mm
Length of the shaft, L	1130 mm
Design Ultimate Load,T	765.21 Nm
Rotation of shaft	3031 rpm

IV. Meshing And Modeling

The subject tail drive shaft is modeled in ANSYS APDL® environment [4] and is meshed using 20-node SOLID186 element. The 20-node SOLID186 element has an advantage regarding the fact that it can easily be molded, has a large amount of key options and therefore addresses a large amount of cases. The ballistic damage is modeled as holes in the shaft at defined locations, the chosen solid element efficiently handles these irregularities in the hollow shaft. Using this element type a total of 265466 nodes are generated. For meshing purpose the Smart Sizing was used and the value was set to 4 after the grid independence was checked that pointed out that the mesh if refined more than this will only take more computing power and less variations in result. The meshed undamaged shaft is shown in Figure 1.



(a)

(b)

Figure 1: (a) Characteristics of 20-node SOLID186 element (b) Meshed Undamaged Tail Drive Shaft

To study the effect of varying impact locations in transverse direction, three different models each with varying ballistic location, are modeled and meshed separately. The ballistic damage is perceived as 12mm hole in drive shaft. Three different cases are modeled which are as follows and are annotated in Figure 2:

(a) Case-1 refers to the ballistic passage through the drive shaft from its center at 350 mm from the fixed support end.
(b) Case-2 denotes the passage of bullet at an offset of 20 mm from the centerline.
(c) Case-3 signifies the chunk removal from end of the circular hollow shaft.

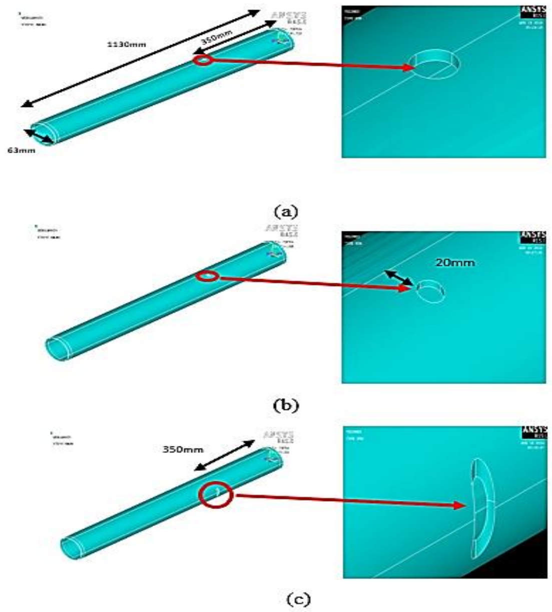


Figure 2 :CAD Modeling of damaged shaft for three different cases (a) Case-1 (b) Case-2 (c) Case-3

V. Load Application

The tail drive shaft transfers the engine shaft power to tail rotor, hence bear the torsional load. The important and critical step for stress analysis of hollow shafts is the application of torsional load. Torsion on a hollow cylinder cannot be applied directly in ANSYS APDL® environment. Two methods that can be used to simulate torsion in ANSYS APDL® are:

(a) Multi Point Constraint Method
(b) Surf element Method

It is to be noted that Multi Point Constraint method is only applicable for the mapped mesh cases, hence not suitable for the case in hand where there is an irregularity in the shaft. Therefore, the SURF element method is adopted. SURF154 is an element that is available in the ANSYS APDL material library that can be overlaid onto a surface and hence surface loads can be applied. However, this has to be carried out after the mesh has been made for the primary geometry, moreover it is used to simulate 3D surface effect and hence can serve our purpose. The load on the shaft is applied in the form of surface load i.e. pressure. Torsional load is applied on one end of the shaft and the other shaft is assigned fix support boundary condition. The application of torsional load is depicted in Figure 3.

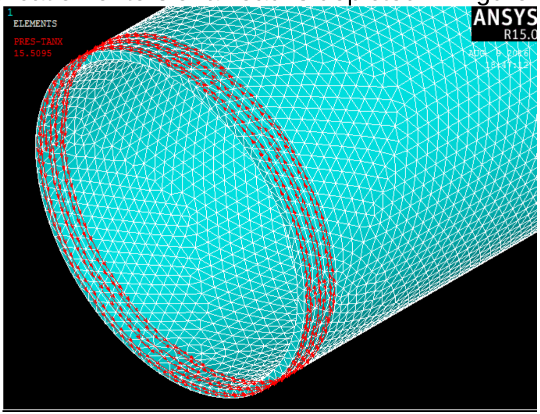


Figure 3 : Torsional load is applied on one end of the shaft using SURF elements

VI. Results and Discussion

In order to validate the FE model for analysis of subject tail drive shaft, the torsional load is applied to the undamaged shaft and the results were validated against the closed form analysis. Analytically, the torsional shear stress as a consequence of applied torsional load is calculated as follows [5]:

$$\tau = \frac{Tr}{J} = \frac{765210 * 31.5}{\frac{\pi * (63^4 - 59.8^4)}{32}} \quad (1)$$

$$\tau = 82.85\, N/mm^2 \quad (2)$$

When the same load is applied to the undamaged shaft using ANSYS APDL® software, the analysis revealed maximum shear stress value in very close approximation to the analytical one, hence validating FE model. The maximum shear stress of undamaged shaft using FE analysis is depicted in Figure 4. Using the same methodology, the stress analysis of damaged tail drive shafts is performed.

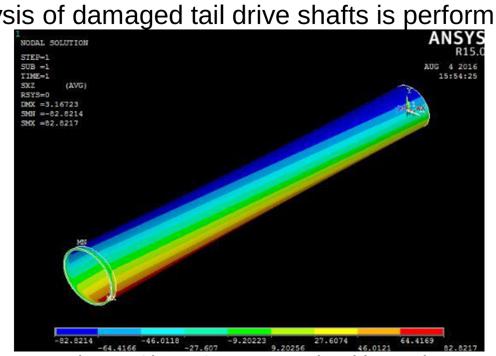
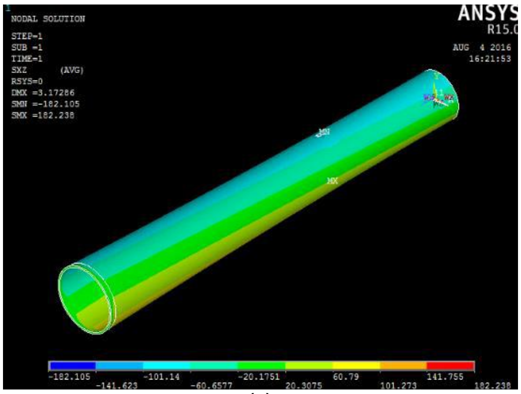


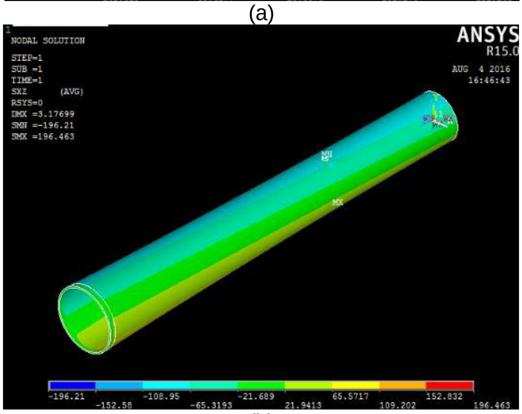
Figure 4 : Maximum Shear Stress sustained by undamaged shaft under Design Ultimate Load

International Journal of Mechanical and Aeronautical Engineering Vol.1, No. 1,September, 2017
© (2017) APISE Press, Hong Kong

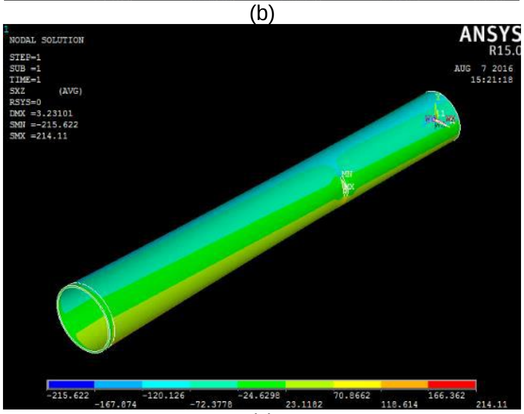
In order to ascertain the torsional strength of the damaged shaft, the ultimate design load is applied to damaged shaft for all the three different cases of damage as discussed earlier. The torsional shear stress and Von-Mises stress distribution for all the three cases are analyzed and are compared with the yield and ultimate strength of the material. The comparison is drawn using the tabular data mentioned in Table 3. The torsional stress and Von-Mises stress distribution for damaged shaft for all three cases is shown in Figure 5 and Figure 6 respectively.



(a)

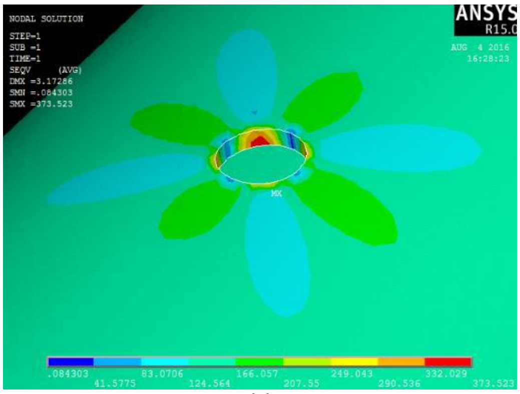


(b)

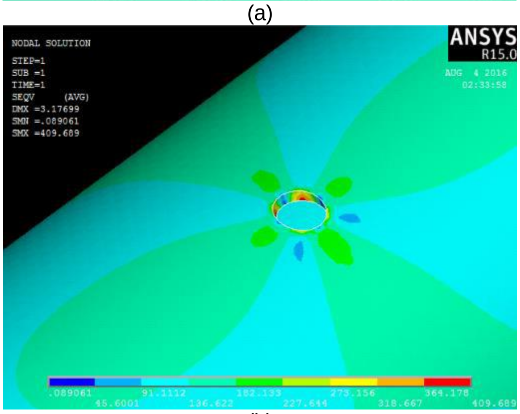


(c)

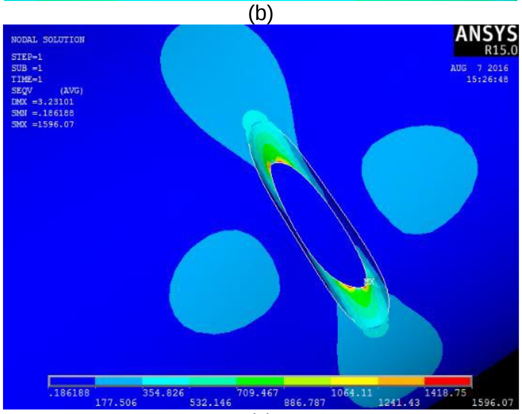
Figure 5 : Shear Stress distribution for damaged shaft under Design Ultimate Load (a) Case-1 (b) Case-2 (c) Case-3



(a)



(b)



(c)

Figure 6 : Von-Mises stress distribution for damaged shaft under Design Ultimate Load (a) Case-1 (b) Case-2 (c) Case-3

The shear stress distribution diagram of the damaged shaft under the pure torsional load indicates that the maximum shear stress lies at the holes (discontinuity) generated as a consequence of ballistic impact which is very much consistent with the theoretical background. The high stress areas around the hole dictates that the fracture will initiate from these surfaces. As only static analysis is carried out, the nature and instant of fracture cannot be ascertained. It is further noticed that as the distance of hole location with respect to shaft centerline increases, the magnitude of maximum shear stress also increases and attains a maximum value for Case-3 damage where a complete chunk of shaft is removed by the passage of ballistic. The analysis of damaged shaft for Case-3 suggests that there would be a severe buckling of the shaft around the penetration due to the presence of compressive stresses. There also lies a mass imbalance in the shaft for Case-2 and Case-3 damage. Under actual dynamic loading conditions, the mass unbalance and the buckling would accelerate the fatigue failure process and seriously reduce the performance of helicopter. The comparison of Von Mises stresses with the yield and ultimate strength of the material is depicted in Table 3.

Table 2 : Strength assessment for damaged TDS (12 mm hole) under Design Ultimate load

Case	Max. Shear Stress (MPa)	Max. Von-Mises Stress (MPa)	Max. Von-Mises Stress / Yield Stress	Max. Von-Mises Stress / Ultimate Stress
1	182.238	373.523	1.098	0.889
2	194.463	409.689	1.204	0.975
3	214.11	1596.07	4.694	3.800

The strength assessment indicates that the strength of Tail Drive Shaft would seriously be compromised as the transverse eccentricity of ballistic penetration increases. This in due to the reduction of mass and generation of compressive stress which cause severe buckling around the damaged location.

VII. Conclusion

The effect of transversely varying the ballistic penetration location is successfully ascertained. If the damage is caused a small caliber penetration, the shaft would have relatively high residual strength, however, in this paper the focus is given to the significant reduction of mass, mass unbalance which significantly reduces the torsional strength of the drive shaft. The farther the location of penetration of ballistic from the shaft centerline, the greater the magnitude of the maximum shear stress will be and chances for failure increases. The maximum damage is suffered in chunk removal case in which the stress concentrations give rise to compressive stresses that cause the shaft to buckle inwards.

VIII. References

[1] CAA Paper 2003/1, *Helicopter Tail Rotor Failures*. Safety Regulation Group, November 2003 ISBN 0 86039 9176.

[2] Kumar, H., *Analysis of Metallic And Composite Tail Rotor Drive Shaft For Ballistic Damage.* International Journal of Mechanical Engineering and Robotics Research, 2015. **4**(1).

[3] Belwagi Gireesh, S.S.B., V.N. Sawtik, *Finite Element & Experimental Investigation Of Composite Torsion Shaft.* International Journal of Engineering Research and Applications, 2013. **3**(2).

[4] *ANSYS Mechanical APDL Basic Analysis Guide.* November, 2013(15.0).

[5] Richard G. Budynas, J.K.N., *Shigley's Mechanical Engineering Design.* 2011.

[6] J.Wang , A.Baker and D. Bitton, *Riveted patch repairs for helicopter tail drive shafts with battle damage,* The Aeronautical Journal, 2014.1188 (1205)

Qasim Zaheer, Assistant Professor, holds a full-time position at Department of Aerospace Engineering, College of Aeronautical Engineering, NUST, Risalpur, Pakistan. He has been working on Computational Fluid Dynamics, Finite Element Analysis and computational analysis of complex flow fields like that of ejector pump..

Abdullah Ehtisham Undergraduate student of Department of Aerospace Engineering, CAE, NUST, Pakistan

Aun Haider. Assistant Professor, holds a full-time position at Department of Aerospace Engineering, College of Aeronautical Engineering, NUST, Risalpur, Pakistan. He has been working on finite element analysis of aircraft wings under different loading conditions