Design of Helicopter Main Drive Flexible Shaft with Hybrid Construction for Weight Reduction

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Abstract

With the advancement of lighter and stronger composite materials over the last decades, metal structures are being continuously replaced by them. Structural members are built with composites with new lamination technologies and the bonding techniques in order to form airframes. In the view of this, the focus of present paper is to look in to the aspect of weight reduction by replacing metallic shaft through composites. Several literatures have demonstrated different composite usage in industry. Drive shaft undergoes twisting moment, so generally unidirectional laminate is not preferred as they may undergo de-lamination during torque transmission.

In the present investigation, analytical calculations were done to find the stresses acting on present metallic flexible shaft. The cross section details and loads acting were obtained from literature survey. Numerical investigation was carried out for the metallic shaft and compared with analytical results. Further analysis was carried out by replacing the existing metallic shaft with woven fibre composites. Validation study for the methodology adopted in MSC NASTRAN was done by comparing the results with literature.

It was observed that the woven fabric in composite have better torque conversion than unidirectional fibres in composite. Metallic shaft was finally replaced by a hybrid construction of steel and woven carbon/epoxy laminate and analysed. Failure analysis was carried out and it was found to be safe under the loading conditions of flexible shaft. This type of construction resulted in around 55% weight reduction for the flexible shaft.

Key Words: Flexible Shaft, Composites, Hybrid Construction, Failure Analysis, MSC NASTRAN

1. INTRODUCTION

A helicopter is a rotary wing aircraft that is propelled by one or more rotors. It consists of two or more number of blades. The primary advantage of helicopter is due to the rotary wing revolving through the air. It will generate the lift so that it can take off and land vertically. It does not require runway for operations. For this reason it is used in isolated and congested areas [1].

Helicopter power comes from piston or gas turbine; it causes to turn the rotor and thus transferring power to the rotary wing. It will undergo aerodynamic loads, bending load and torsional loads. With the advancement of lighter and stronger composite materials over the last decades the power transmitting shafts which are being replaced with composites. The disadvantages with composite shafts are the joining issues and de-lamination due to torsional loads. There are many numerical methods, which are used to design and analyse optimum composite drive shaft in order to reduce the weight

A drive shaft of hybrid composite construction with carbon and glass fibre with epoxy resin was analysed [2]. Hybrid configuration was constructed by wrapping carbon/epoxy and glass epoxy with stacking sequence of [45°445°490°490°4] on aluminium shaft. Strength of the shaft was dependent on the stacking sequence. The analysis was carried out for an automotive drive shaft

Effect of the fibre orientation angle was studied. Since matrix form of the equation contains stiffness and mass matrices it was concluded that stacking sequence had no effect on the natural frequency.

In another work, aluminium/composite hybrid shaft was developed by S. A. Mutasher to predict torsional strength of the drive shaft [3]. He investigated the maximum torsion capacity of aluminium/ composite hybrid shaft. It consists of carbon fibre/epoxy and glass/epoxy composites wounded on the aluminium hollow shaft. He analysed the shaft for different winding angle, number of layers and stacking sequences. He concluded that increasing the number of layers can increase the static capacity of hybrid construction for both carbon and glass fibre composites. It was also noted that stacking sequence of [90/+45/45/90] and [+45/45/90/90] gives the same behaviour of torque angle of twist.

Composite unidirectional (UD) laminates are found not suitable for shaft because it is poor in torque and delamination will take place. Hybrid configurations are employed for better performance than composite alone. Composite woven fabrics are having better strength than UD laminates; it exhibits almost same Young's modulus in both the directions. In the present work plain woven composites are laminated on metal shaft and analyzed for different loading conditions to find the optimized hybrid construction.

2. METHODOLOGY VALIDATION FOR COMPOSITE MODELING

Flexible shaft is a rotating member having circular cross section used to transmit the power from engine to rotor blades. Important parameters to be considered for design of flexible shafts are selection of materials, geometric layout, stress, deflection under torsion and bending. Shaft sizing is necessary to realize the stresses acting on it. Deflection analysis has to be carried out after determining the size of the shaft. Deflection is a function of entire geometry, but stress is function of local geometry, thus after establising the geometry, deflection has to be analysed for sizing the shaft.

2.1 Methodology validation for woven composites

For the purpose of validation, a methodology developed by Li et.al.,[4] to analyse circuit board made from woven fabric composite subjected to bending was chosen.

Displacement from FE analysis was compared with literature result. Negligible variation was found from analysis. Comparison of literature and analysis are shown in the Fig. 1. It shows that plain weave composite analysis by using MSC Nastran is reliable and this was thus used for thesis work.

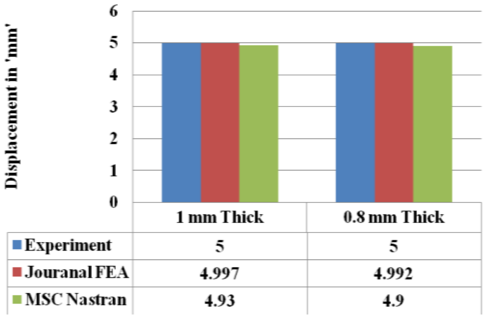

Fig. 1 Thickness versus displacement for woven fabric composite

2.2 Comparison of Plain weave composite with Unidirectional Composite

Fig. 2 shows the Principal stresses for printed circuit board induced in each ply. It can be noticed that induced stresses in each layer is less in plain weave composite than the unidirectional laminate. From the result it can be concluded that woven fabric gives better strength than UD laminate. For hybrid construction of flexible shaft, it can be incorporated. Validation of results will be baseline for further analysis in MSC Nastran.

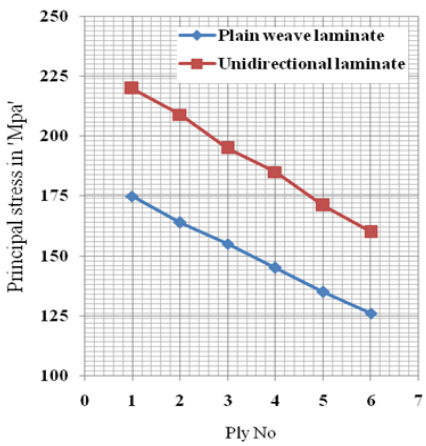

Fig. 2 Comparison of principal stress versus ply number

3. FINITE ELEMENT MODEL DEVELOPMENT

3.1 Geometry modelling

Geometric model required for analysis of main rotor flexible shaft is as shown in the Fig. 3.

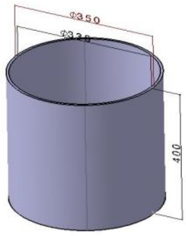

Fig. 3 Cross section of flexible shaft

3.2 Finite element model and load application for steel shaft

Finite element model was created using MSC Patran. Then model was descritized in 1200 elements by using quad elements

The boundary condition consists of one end of flexible drive shaft been fixed to output drive shaft and another end attached to rotor blades.

The rotor system loads for main rotor were generated by the rotor blades. The total load acting is a of sum of aerodynamic, centrifugal, inertial, torsional shear loads and gravitational forces and their respective proportions will vary under different conditions. When the helicopter is on the ground with its engine stopped then blade weight is the only load. When the rotor is spinning but providing no lift, the predominant load is centrifugal [5].

For structural analysis, centrifugal force is considered as bending load. Torsional load will be acting from power transmitted from engine, so torque is considered as torsional load. The applied loads for analysis was calculated and tabulated as in the Table 1.

Table 1 Details of applied load on the shaft

Axial load	55000 N
Bending load	594146 N
Torsional Load	$217x10^6$ N-mm

Finite element model of the flexible drive shaft with applied load and boundary conditions is as shown in the Fig. 4.

3.3 Finite element modelling of hybrid flexible drive shaft

Hybrid construction was made by steel and Carbon/Epoxy composite. Hollow steel shaft Ø342X400 with the thickness of 2 mm was modelled. Above this shaft 4 mm plain weave composite was wrapped on metallic shaft as shown in Fig. 5.

Green colour shows the steel portion, yellow portion shows the composite laminate. Geometry of model was built and descritized into 2400 elements by using quad4 2D elements.

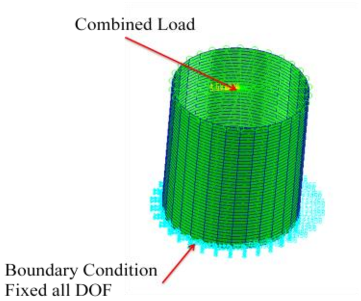

Fig. 4 FE model with applied loads and boundary conditions

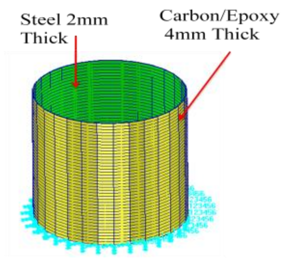

Fig. 5 FE model of hybrid flexible drive shaft

Analysis was carried out and Principal stress and displacement for both [(0°X90°)]32 and [(+45x-45)1]s orientations were found out by numerical simulation.

4. RESULT AND DISCUSSION

4.1 Comparison of results

Table 2 shows that [(+45°/-45°)] has more displacement and stress than [(0°X90°)], so [(0°X90°)] orientation is suitable for hybrid construction.

Table 2. Comparison of results for different combinations

	Material	Max. Principal stress,	Displacement, mm
Existing steel shaft	**Steel**	**654 MPa**	**1.98**
Hybrid (2mm steel) [(0°90°)]	**Steel/ Carbon/ Epoxy**	**1230 MPa**	**4.29**
Hybrid FEA (2mm steel) [(+45°/-45°)]	**Steel/ Carbon/ Epoxy**	**1450 MPa**	**4.56**

4.2 Selection of hybrid configuration

Structural analysis was carried out to ensure that hybrid construction will not fail under defined loading conditions using reserve factor. Composites construction was checked against the failure using Tsai Wu failure criteria. The details of reserve factor for different configurations are shown in Table 3.

Table 3. Comparison of calculated values of reserve factor

Shaft type	Reserve factor
Existing steel shaft	**1.58**
Hybrid (2mm steel) [(0°90°)]	**0.84**
Hybrid FEA (2mm steel) [(+45°/-45°)]	**0.712**

From the analysis it was found that failure index is less than 1 in each layer and maximum failure index is 0.435 shown in the Fig. 6, hence composite will not fail under this combined loading condition in [(0°X90°)] orientation.

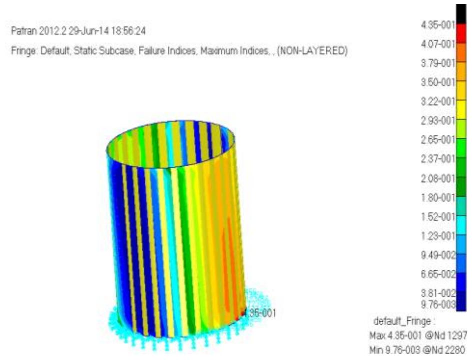

Fig. 6 Maximum failure indices of composite

[(+45°/-45°)] laminate failed at all layers, because failure index is more than 1 as shown in Fig. 7 so this construction will fail under applied loading conditions.

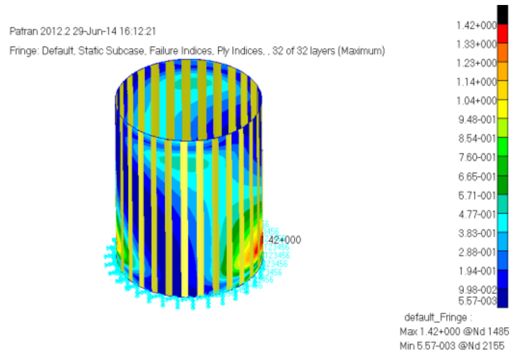

Fig.7 Failure indices for [(45X45)] orientation

4.3 Comparison of Weight

Once the design and failure analysis was done, weight was calculated to determine the percentage of reduction in weight.

Weight of existing steel shaft was calculated and found 10.94 kg and hybrid construction was found that 4.94 kg, there was 54.84% of weight reduction in hybrid [(0°x90°)] construction and also it has better stiffness than the [(+45°/-45°)]. It is most suitable construction for the helicopter main rotor flexible shaft.

4.4 Buckling load and analysis

Due to torque transmission from input to output, it will experience the torsional buckling. There is a chance of buckle in the shaft; to avoid this structure must be strong enough to with stand the toque. For this purpose, finite element buckling analysis was carried out in MSC Nastran and buckling factor was found out.

Buckling factor is found to be 1.02 as shown in the figure 8. Hence it can be concluded that the hybrid configuration can withstand the buckling factor's times the load.

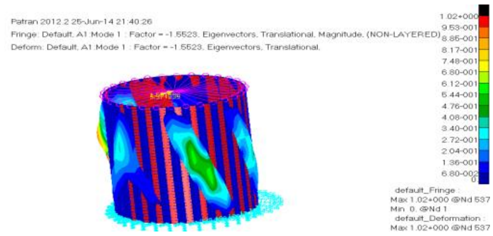

Fig. 8 Buckling analysis results

5. CONCLUSIONS

- Hybrid construction of steel and carbon/epoxy with the layer orientation of [(0°X90°)] is suitable for particular 5K class of Helicopter.
- Plain weave Carbon fibre has very good torsional stiffness. Fibre orientation of ±45° experienced failure in all layers. Optimum stacking sequence is 0° and 90° for power transmitting shaft
- Weight is reduced more than half of the existing steel shaft. This can be extended to all primary structural components in helicopter; hence weight optimization can be done for whole Helicopter.

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