FEASIBILITY STUDIES ON POWER TAKE OFF COMPOSITE SHAFT

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ABSTRACT: Polymer composites are today widely used for aerospace components in view of their outstanding specific stiffness and strength to weight ratio. This paper provides details related to the design of a carbon composite hollow torque transmission tube for a pre-specified value of torque, geometrical constraints and torsional rigidity, which could be useful as a power take off (PTO) shaft segment. This paper also gives the details of the test rig designed and fabricated for the purpose of testing composite hollow tubes. The test results provide details related to torsional rigidity and torsional deflection as a function of load. The composite tubes were fabricated using filament winding technique. The study has indicated possibility of using carbon composites for typical aerospace component like a torque transmission tube with weight and cost benefits without compromising on the shaft dynamics. Experiments were also conducted to study the effect of ballistic damage on the composite shaft and also the damage tolerance related to misalignment. This effort has provided enough confidence level in attempting the replacement of existing metallic shaft by composite shaft for PTO shaft application.

KEY WORDS: Power Take off Shaft, Carbon Composite, Torsional Stiffness, Misalignment, Ballistic Damage

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1 INTRODUCTION

Off late composites are being used for realizing rotating components and as such research activities are on the rise in this area. A brief literature review has been presented in the following. De-lamination propagation in rotating carbon-epoxy composite shaft was studied [1], wherein a carbon-epoxy shaft was fabricated by filament winding technique. De-laminations are introduced during fabrication and the composite shaft was subjected to cyclic loadings because of unbalance excitation. The de-lamination zones were radiographed to determine the crack extension. Co-cured extension-twist coupled damped composite torsion shaft was studied [2], wherein co-curing layers of visco-elastic damping materials with composite material system offers the possibility of manufacturing light-weight, stiff, highly damped structural components. The main objective of this referred work was to design an extension-twist coupled damped composite torsion shaft and compare its performance against a damped shaft that uses a floating constraining layer to enhance damping performance. Stiffness identification of laminated composite shafts was studied [3], wherein distribution of the bending stiffness along the spans of laminated composite shafts are determined via a non-destructive evaluation approach. Optimal design of composite power transmission shafting was studied [4] ,wherein it was concerned with the replacement of a conventional drive shaft system with a composite system which transmits the same power. Most of the shafts are being fabricated with filament winding technique and as such number of fiber inputs play a dominant role in their performance defined in terms of torsional stiffness. An attempt has already been made in this regard to study the effect of number of fiber inputs by experimentation apart from studying the effect of various other related parameters [5,6]. The basic aim was to design hollow torque transmission tube for a particular application, wherein the requirements are clearly defined along with ballistic damage effects and misalignment effects on torsional stiffness. The specification details are given in Annexure1.

2 METHODOLOGY

The theoretical analysis was based on a layer upon layer basis with a view to obtain the optimum range for the number of layers satisfying the torsional stiffness, strength and weight requirements of the composite shaft. Since the process of filament winding technique does not lead to a definition of a layer in view of the fact that the fibers are entangled with each other in axial and radial directions, and based on the earlier experience it was thought fit to use ten number of fiber inputs during fabrication. It may be noted here that layer to layer separation is observed only when the combined width of all fiber inputs would be equal to one pitch (which depends on fiber orientation angle), since one pass of the carriage carrying the fibers will cover the entire mandrel and hence the reverse pass of the carriage will give totally a new layer. This leads to the fact that in case the combined width of the fiber inputs is less than one pitch, the mandrel will not be covered in one pass, so that number of to and fro passes required depends upon the combined width of fiber inputs in relation to the pitch. Alternatively, it can be said that lesser the number of fiber inputs more the number of to and fro passes required to cover the mandrel surface once completely. The effect of ballistic damage and the misalignment were viewed purely experimentally. Holes of different diameters were drilled and the effect of the damage caused by the hole (simulated to a ballistic to the extent possible) on the torsional stiffness could be obtained. Similar approach was followed to obtain the effect of misalignment on the torsional stiffness.

3 EXPERIMENTATION

A Static torque test rig was designed and fabricated for the purpose of testing composite shafts in order to obtain the torsional deflection and hence the torsional stiffness, when the specimen is subjected to pure torsional load. The test rig consisted of two brackets one in which the test specimen could be fixed rigidly and the other in which test specimen could be supported on rolling element bearing mounted in the bracket. The position of these two brackets could be adjusted to any desired length to cater to different lengths of specimen and also to facilitate assemble the loading mechanism. The purpose of rolling element bearing was only to support the test specimen practically offering no torsional resistance thus resulting in complete reaction for the loading offered by the fixed end only. The loading mechanism basically consisted of two loading arms, which could be assembled to one end of the test specimen projecting out of the rigid bracket supporting the rolling element bearing. The two loading arms are loaded at the ends using dead weights in such a way that the specimen is subjected to pure torque. The photograph of the rig is shown in figure 1. Instrumentation basically included the measurement of angular twist evaluated through the vertical deflection of the two loading arms. Arrangements were made to obtain torsional deflection at any desired location along the specimen axis. Torsional stiffness was quantitatively evaluated using the measured data.

4 RESULTS AND DISCUSSION

Composite hollow shafts of carbon fiber reinforcement [E_{11}=112.5 Gpa, E_{22}=5.43 Gpa, G_{12}=2.23 Gpa, ν_{12}=0.29] were fabricated by filament winding technique. Various parameters were considered to study their effect on the shaft strength defined in terms of torsional stiffness. The factors considered includes number of layers, fiber orientation angle etc, the effect of each of which along with the effects of simulated ballistic damage and misalignment is discussed in the following paragraphs.

Preliminary design efforts for obtaining optimum range for number of layers:

FEM analyses were performed with a view to obtaining the optimum range for the number of layers (starting from 12 up to 24 layers) with various fiber orientation angles (starting from 0 up to 90 degrees, angle measured from the vertical) keeping inner diameter constant. The results are graphically shown in figure 2. It is clear from the figure 2 that torsional stiffness would reach a maximum when fiber orientation angle is 45 degrees. Similarly a plot of maximum torsional stiffness, weight and stress along fiber direction v/s number of layers is shown in figure 3 which indicates that as number of layers increases, while the stress decreases, weight and torsional stiffness increases. The minimum value of the torsional rigidity and maximum values of weight and resulting stress are also indicated in figure 3. It is clear from the figure that the number of layers cannot be less than 16 layers since torsional rigidity would be below the minimum required and also cannot be more than 24 layers since weight of the shaft would exceed the limiting value. As such the number of layers would have to be chosen in this range.

Torsional stiffness:

Two carbon fiber reinforced plastics tubes of outside diameter measuring 48mm and 50mm (suiting to the existing dimension of the metallic PTO shaft) were fabricated and tested for obtaining the torsional stiffness. The CFRP torque transmission tubes were tested up to 1147 N-m (the required torque was 1000 N-m). Figure 4 shows the torsional stiffness offered by the two tubes with outer diameter respectively being 48 mm and 50 mm (the inner diameter being 43.5 mm and effective length being 376 mm for both) from which it is clear that the stiffness is almost constant as a function of load indicating the linear behaviour of the CFRP tubes. The torsional stiffness offered by the two fabricated shafts, is more than that required for the application. Figure 5 indicates the torsional deflection along the shaft axis, which shows that the behaviour of CFRP tube is linear defined in terms of the angular twist as a function of axial length. This indicates the quality of fabrication achieved during filament winding technique.

Effect of ballastic damage:

The effect of ballistic damage was studied by drilling holes, the diameter of which were equal to holes that could be resulted by bullet. The tests to study ballistic damage and misalignment are conducted on CFRP shafts with length 1147 mm, ID 60 mm and OD 65 mm suiting to tail rotor application in helicopters. Although exact simulation would not be possible (the bullet might cause a damage slightly more severe as compared to a conventional drilled hole) the study was conducted by varying the hole diameter and the number of holes. Figure 6 shows the variation in torsional stiffness for different hole diameter and for different cases including the through hole case (as if the bullet has completely pierced through the tube). It is clear that while torsional stiffness has not changed much for a reasonable degree of damage (for the case of a through hole of 12mm diameter). However the stiffness decreases drastically when multiple holes are drilled. The spacing between holes were random since the stiffness of each shaft portion in between the holes would act in series with the neighbouring ones and as such area of cross section where the ballistic damage has occurred and the number of ballistic damage would dominantly control the net effective stiffness. The composite shaft with multiple holes failed at 1147 N-m torque level. The study indicates that carbon composite shafts are as tolerant to ballistic damage as the metallic shafts.

Effect of Misalignment:
The effect of misalignment was studied by realizing the required height difference between the two ends of the tube and then subjecting the tube to the required torsion in order to obtain the torsional stiffness under axial misalignment. Figure 7 shows the variation of torsional stiffness as a function of misalignment. It is clear that while torsional stiffness does not reduce noticeably with increasing misalignment up to a reasonable level. However the performance drastically reduces for a very high degree of misalignment. The shaft failed at torque level of 998.67 N-m for 1.51 degree misalignment. Nevertheless the performance of composite tube matches with that of metallic tube. CFRP tubes of length 1114.5 mm and inner and outer diameter of 59.6 mm & 64 mm respectively was used for this purpose.

5 CONCLUSIONS
An attempt has been made to design, fabricate and test composite hollow shafts to be used for airborne applications, such as PTO shaft segment, keeping in mind the benefits obtained in terms of reduction in weight and cost of manufacture. Two CFRP shafts were fabricated using filament winding technique and were tested in a test rig built for the purpose. Considerable weight benefits have been obtained to the extent of a minimum of 35%. Effects of ballistic damage and misalignment have also been obtained. This feasibility study promisingly indicates that carbon fiber hollow shafts can replace metallic shafts for PTO shaft applications without any compromise from torsional stiffness point of view and with weight benefits.

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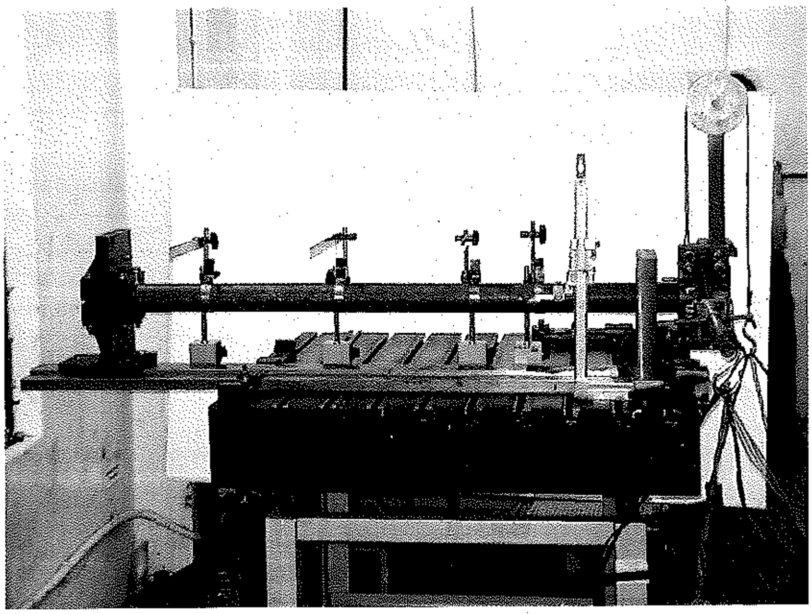

Fig. 1 Photograph of the Static Test Rig

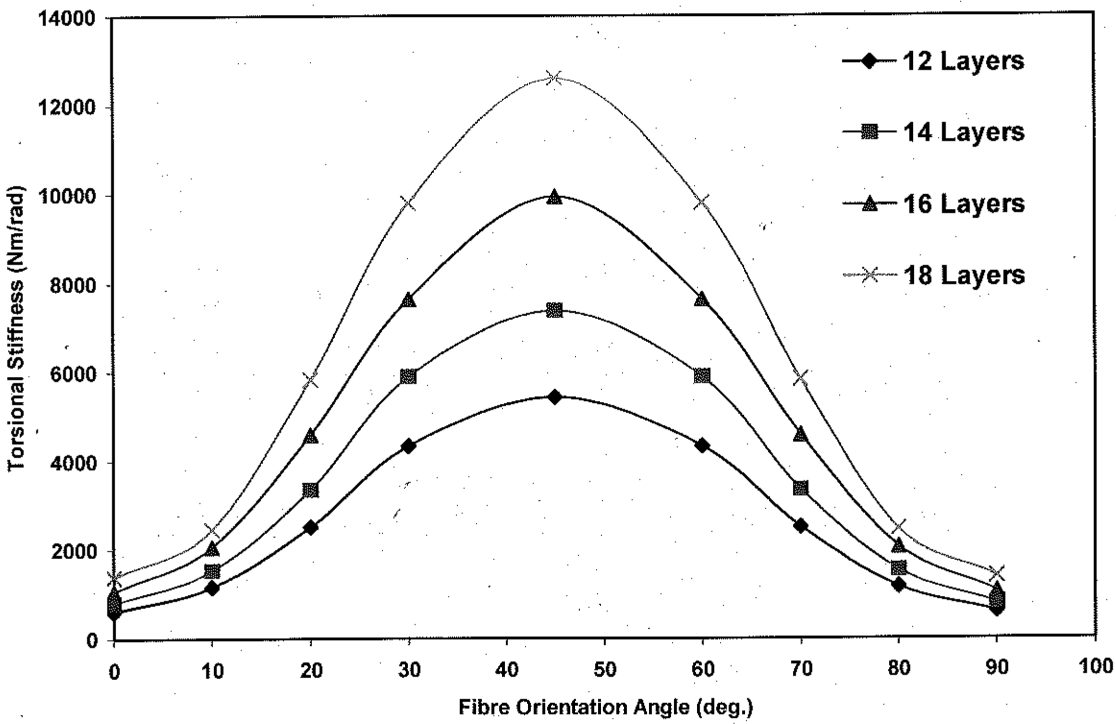

Fig. 2 Effect of Fibre Orientation Angle on Torsional Stiffness

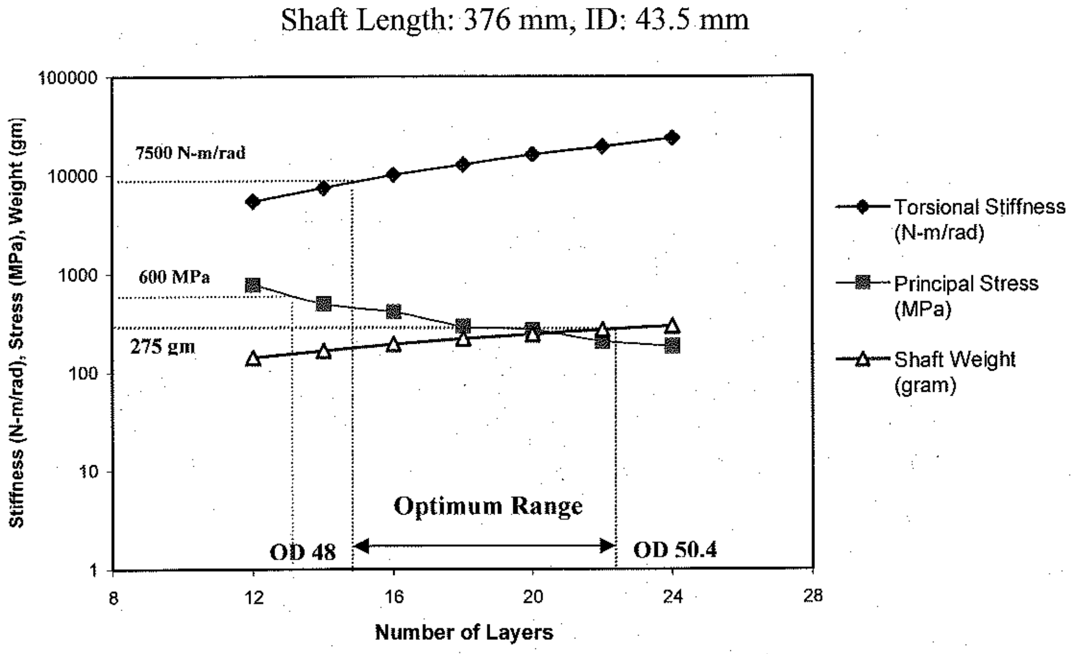

Fig. 3 Effect of number of layers on torsional stiffness, stress and weight of the CFRP shaft

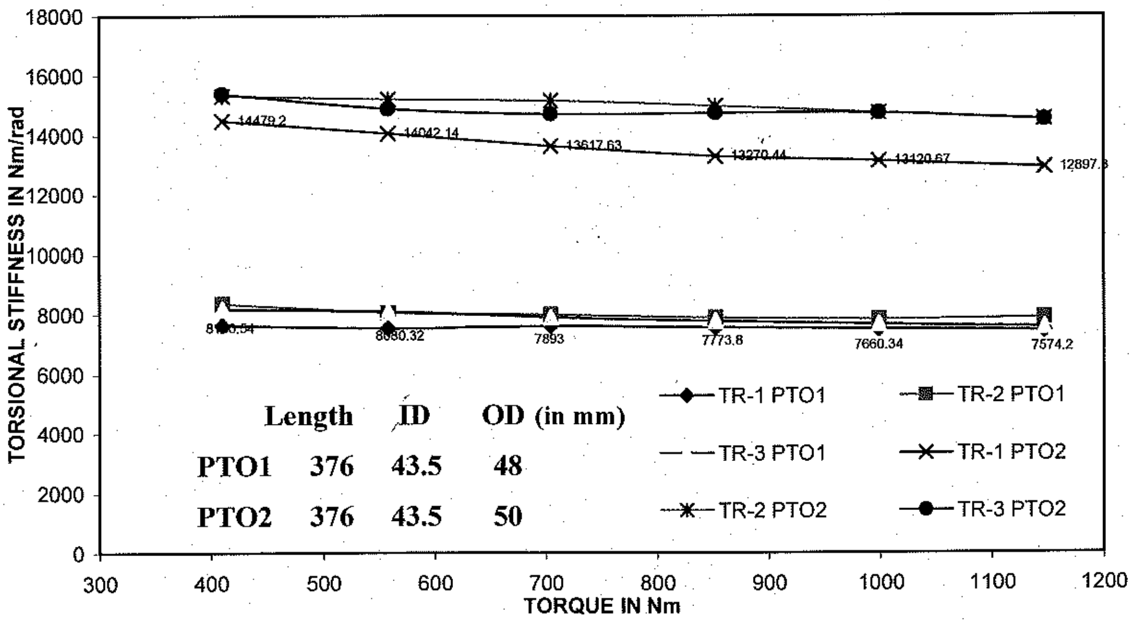

Figure 4. Torsional Stiffness of PTO Shaft Segment 1 & 2

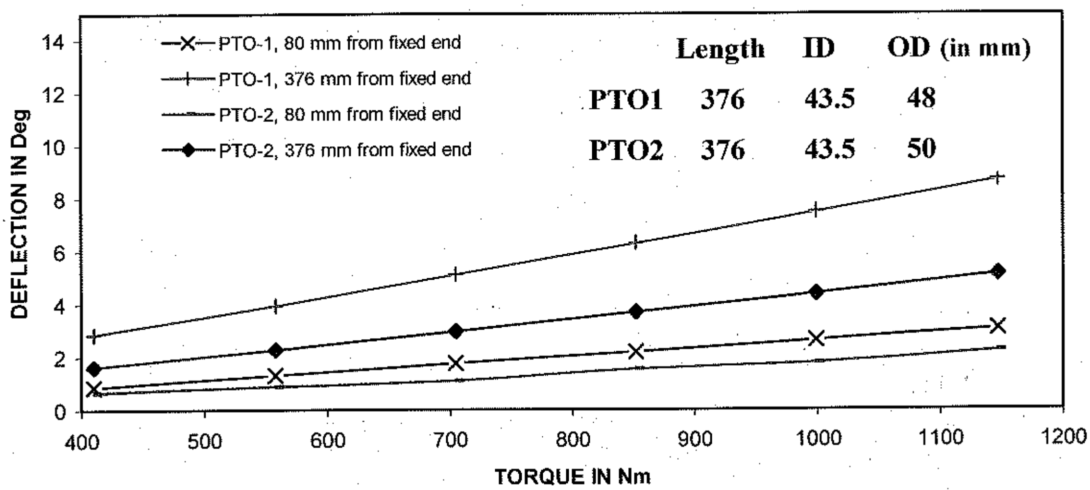

Figure 5 Torsional Deflection along the Shaft axis under Static Torque

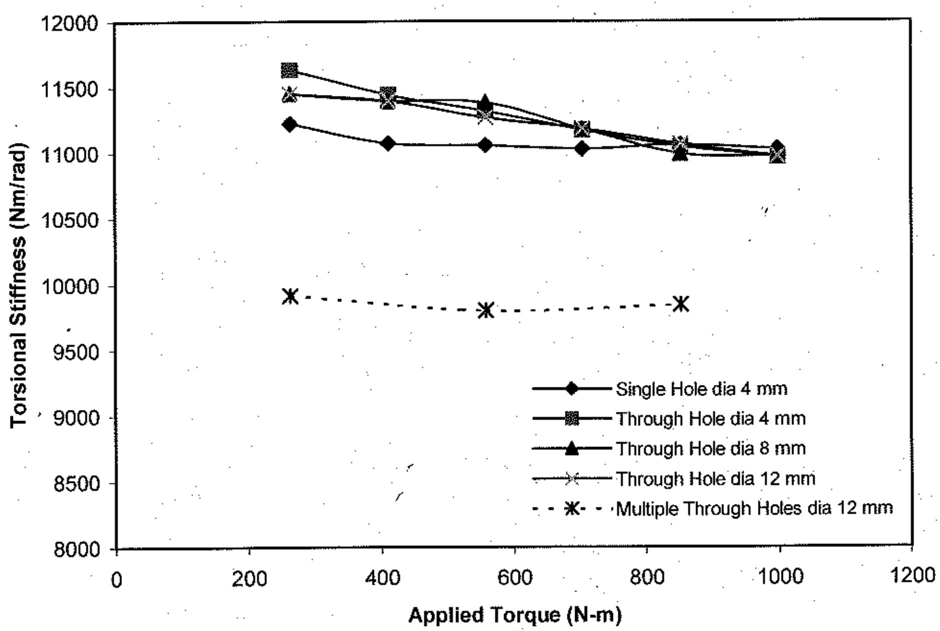

Fig. 6 Effect of Simulated Ballistic Damage on Torsional Stiffness

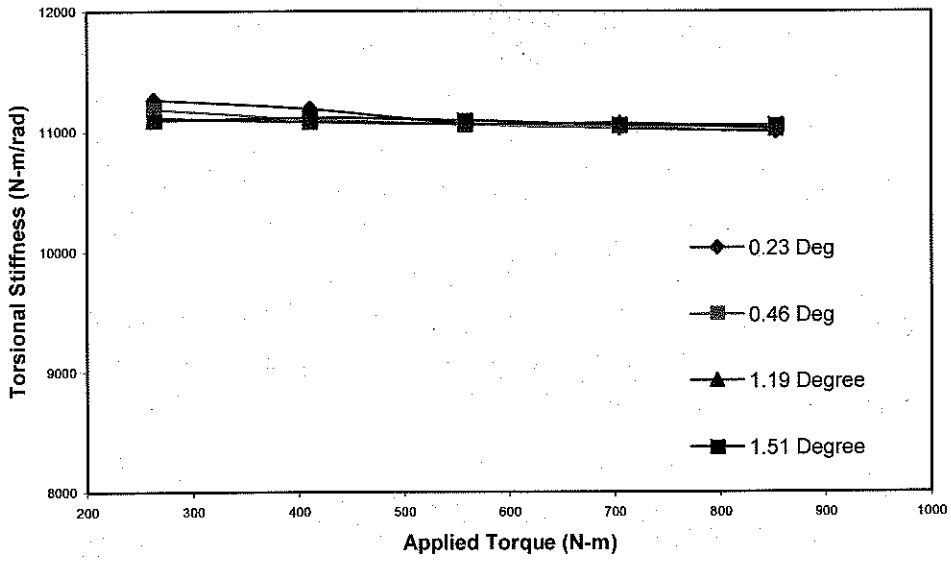

Fig.7 Effect of axial misalignment on torsional stiffness

Annexure-I

Shaft length	**: 376 mm**
Shaft ID.	**: 43.5 mm**
Min. Torsional Stiffness	**: 105 Nm/deg.**
Max. Weight	**: 296 gms**