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Development of a Co-cured Composite Torque Shaft for Rudder of High Speed Aircraft

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Abstract

The Carbon Fibre reinforced Composites are widely used in developing various composite parts of civil and military aircraft due to its high specific strength and specific stiffness. Rudder being a primary control surface in an aircraft, it is subjected to various loads and needs high degree of structural integrity. Usually rudders are made of metal with many fasteners. In NAL we have designed and developed a composite rudder. Specialty of this rudder is that it has a torque shaft made up of carbon composite and has only few rivets. Conventionally torque shaft s are made up of special metals like titanium. The objective of this paper is to highlight the development of various tooling techniques used to fabricate the composite torque shaft . All major parts of the torque shaft are made by Co-curing technique and the metal attachments are embedded to the composite parts by self locking mechanism design. To qualify the torque shaft fatigue tests are done and ageing studies performed to prove structural integrity of the torque shaft under extreme environmental conditions. This paper portrays the development efforts, tolling and fabrication approaches for successful realization of the CFRP Torque Shaft.

1.0.Introduction

Aircraft designers and manufacturers are concerned with the all up weight of the aircraft and always try to reduce the weight. In the cost of aircraft with less process and manufacturing cost. One approach is to reduce the aircraft weight by reducing the structural weight. Here effort has been made to reduce one of the control surface (Rudder) weight. During this process, a weight saving of 20 % is achieved. The initial design envisaged a honeycomb structure at aft box side of Rudder, but this was abandoned due to high maintenance cost resulting from the anticipated high impact damage and the another concern was that ingression of moisture in to a honeycomb core, which affects the structural performance of rudder. Hence decided to follow the classic multi-rib substructure concept with aft spar assembly, and also replacing titanium torque shaft (Fig-1) to CFRP torque shaft assembly.(Fig -2). Titanium torque shaft machining consumes more time, need a special purpose machines, cutting tools and a laser beam welding to connect to torque tube with skin area, which is need to be qualified by X-ray. Ultimately process time and cost will become very high. Replacing with CFRP torque shaft assembly is the most challenging work. It is a stress critical part and also it has a hinge point, maintaining a hinge line is a most difficult task of this development.

Fig-1. Titanium Torque Shaft Assembly

Fig-2. CFRP Torque Shaft Assembly

The rudder assembly consist of the two skins, front and aft spar assembly, co cured sub structure assembly, co-cured torque shaft assembly and nose box assembly. These parts are integrated using adhesives and mechanical fastening methods. In total only 4.5 % of weight is the metallic component weight, remaining all CFRP material. Since advanced composite division of National Aerospace Laboratories have developed many aircraft structure for military aircraft using advanced composites, the advancements in the manufacturing process like co-curing & co bonding are familiar to realize the composite structure of less weight and low cost.

Finally co-curing technology has been selected to develop this CFRP torque shaft assembly. Three such CFRP torque shaft assemblies have been manufactured and tested to meet the requirements of a fighter aircraft. In this paper, the authors try to bring out the salient features of tool design for complex parts, various manufacturing process and its problems.

2.DESIGN PHILOSOPHY

The schematic diagram of CFRP torque shaft is shown in figure-3. Fabrication of co cured structure is a recent technique in the fabrication of composite component. To meet the structural strength and stiffness requirements of the torque shaft the size and geometry have been extended than titanium torque shaft. The hinge attachment points of torque shaft have been designed by titanium metallic materials. Tube and horn assembly was designed to take torsional loads and compressive loads. Skin with integral ribs construction was designed to the aerodynamic loads and give sufficient stiffness to the structure. The extended torque shaft skin surface was increased, to increase the load transfer area. Design & Analysis was carried out using ELFINI FEM software. The material was selected on the basis of functional, environmental and loading requirements. Unidirectional prepreg of carbon fibre T300H is used for torque shaft development. This prepreg has a epoxy based resin system, which is used for all other rudder sub assemblies (I.S Skin, Spar etc.). Tube and horn assembly made out of +45° / -45° UD tape layers only, where as the skins and ribs are made using quasi isotropic lay up sequence. The rudder actuator attachment points are provided with titanium material to provide better wear resistance and minimize the coefficient of thermal expansion. In general three types of composite –metallic adapter joints are employed by conventional drive shafts such as fastener joints, serration joints and bonded joints [2,3]. The new design concept was achieved by using octagonal shaped spindle bonded joint design is adopted [6]. The 6mm width of U.D. tape is laid up and cured, in which spindle will is interlocked inside the tube (Fig- 4). The metallic parts are bonded using epoxy based film adhesive. In accordance with design, detail component drawings are generated containing stacking sequence, layer drops and references with respect to rudder axis.

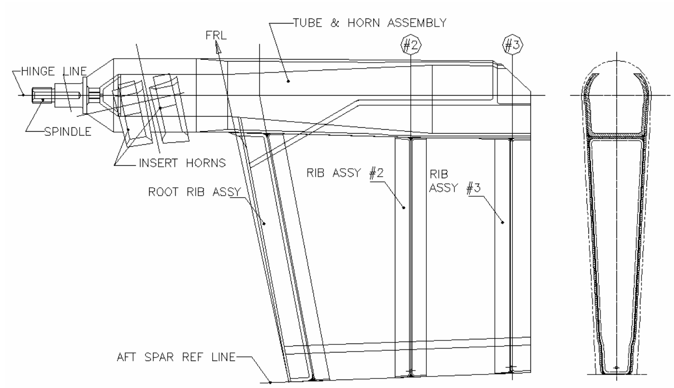

Fig-3 Schematic Diagram of CFRP Torque shaft.

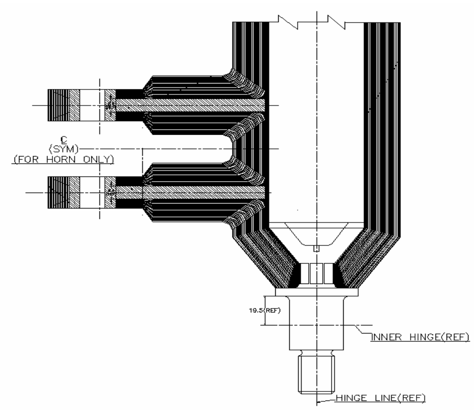

Fig-4 Tape Lay up over the metallic parts.

3.CONFIGURATION

With respect to configuration of torque shaft has an overall size of 600mm X 400mm X 150mm. It consists of one tube and horn assembly with three titanium metal parts, CFRP outer skins with integral 'I' section ribs. Rib assemblies are having variable thickness in flange & web. The skins are having thickness variation from 2.4mm to 3.6mm to match I.S. Skin thickness. All these items are Co-Cured together.

4.DESIGN & DEVELOPMENT OF TOOLING.

Tooling Technology is fundamental to the production of a good quality part and as material developments occur, parallel developments in tooling technology are required to ensure that the tools can withstand the process requirements. The torque shaft assembly mould is fabricated using composite material.

This main moulds is most critical, because the component outer profile is directly proportional to the tool surface. Composite mould has been fabricated to get better aerodynamic profile and also this offers advantages of a good thermal conductivity for obtaining acceptable heat up rates in curing under 7 bar external pressure. The other major benefits of composite tools are that they can be fabricated any complicated shape of large tool surface with comparative ease and at faster rate. The dimensional accuracy of the tool surface is derived from the master model. The matched die mould concept is used. Several tools and fixtures had been designed & manufactured to meet the critical dimensional requirements and also uniform heat conduction during curing process. Some of the other tooling concepts have been used in the development process, which are described below.

4.1 SAND MANDREL CORE

Sand mandrel core is designed based on the internal dimensional requirements of tube and horn assembly. One popular method is using dissolvable core method, to create a hollow sections. The main design consideration for this core is that when 7 bar autoclave pressure is applied on the mould, with out undergoing much deformation mould should be closed. This condition ensures that the laminate is under full pressure.[5] The real problem in this sand mandrel core is that the laminate thickness varies according to compaction variation during curing, but in this torque shaft at root side tube has 20mm thickness and at Sta #3 side is only 6 mm thickness. Hence while designing this Sand –PVA core, the required tolerance is provided to get sufficient pressure, by taking advantage of core expansion. Sand mandrel cores are used here to get extra pressure from inner surface of laminate and also it acts as a lay up tool, for winding of +45° / - 45° layers. This sand core will be removed by dissolving in water, after curing. The titanium spindle act as inner hinge locator in the rudder assembly. The inner hinge spindle is bonded in the Sand –PVA core by using spindle bonding fixture. Bonding of this spindle is most critical one, because this need to be bonded with ± 50 microns accuracy. This spindle is designed in such a way that the centre line offset will not occur during bonding of spindle. Sand –PVA core is fabricated after bonding of spindle in a centre rod. Then core surface finished and covered by release film.

4.2. ALUMINIUM POWDER CASTED CORES

This Aluminum cores are fabricated using powder metallurgy concept. The only difference is that epoxy based bonding material is used to cast this core. The very fine aluminum powders are mixed with epoxy based resin & hardener mixture and casted the CFRP mould at room temperature. After cure at room temperature and post cured as per bonding material manufacturer's recommendation in the oven. These aluminum cores are designed by considering thermal expansion of core, heat conduction, capability of dimensional retention etc. These cores are used as lay-up tool for root and Sta #3 ribs assembly of torque shaft. The required thermal expansion allowance have been provided in these cores. Lay up area of these core are covered by 3mm thickness of silicon rubber caps (Fig- 5). The silicon rubber exerts a pressure under the heat due to its expansion, which is used to apply pressure from inner surface of the rib assemblies.

Fig-5. Aluminum core with silicon rubber cap

Fig-6 Silicon rubber tubular bag

4.3. SILICON RUBBER TUBULAR BAR

Silicon rubber tubular bags are used between Root O/B to Sta #2 I/B box and Sta #2 O/B to Sta #3 I/B box area, to provide positive pressure from inner surface of the components (Skin & Rib Assembly). Aerodynamic profile of the torque shaft has been controlled by the torque shaft moulds, hence internal dimension of the torque shaft is not much critical. Hence silicon rubber tubular bags are used in the inner surfaces. These silicon rubber tubular bags (Fig-6) are fabricated with steel nipple to exert a pressure from inner surface, while curing. Steel nipples are embedded in the wall of the silicon tubular bag. The advantage of these bags are, they will undergo large elongation with out failure, which gives pressure from inner surface. The elongation property varies based on mixing of base material and hardener, which will intern affect the viscosity of mixed material.

4.4.SKIN LAY UP FIXTURE

This skin lay up fixture is essential to join tube and horn assembly with skin of torque shaft assembly. The fixture is also to control the outer boundary of the torque shaft, Position of the rib assemblies and also it facilitates the torque shaft skin lay up process. Rib assemblies and Tube & horn assemblies are integrated using this assembly fixture.

5.FABRICATION ASPECTS

Numerous methods of traditional composite fabrication were studied, and finally it was decided that a parallel path fibre placement concept had been adopted for tube and horn assembly. The torque shaft tube has thickness variation from 6 mm to 20mm. The titanium material spindle is embedded with carbon UD prepreg using film adhesive Redux 319A. After 14 layer of tube winding, insert bottom & Top horns have been fixed over the tube lay up using positioning fixture.(Fig- 7) These horns are also bonded with UD prepreg using film adhesive redux 319A. Hoop winding is carried out on the metallic parts of horns and other area of tube is cross winding by +45° and -45° ply angle. The cross winding by +45º & - 45º is the most difficult task, because the end of the part tape may slip from the metal parts. This winding process carried out using winding fixture.(Fig-8) After completion of tube and horn assembly winding process, this will be assembled in the skin lay up fixture along with Sta #2 rib assembly and its pressure pads. Tube assembly web and Sta #2 rib assembly web bonded together. The skin lay up can be carried out over this fixture.

Fig -7. Positioning of Horns over the Tube Assembly

Fig -8. Tube Winding Fixture with Tube&Horn Assy

Root rib assembly, Rib assembly Sta #3 have been laid up over the aluminum powder casted core. The I/B side & O/B side of the rib assembly are laid up separately and bonded together out side . This root & Sta #3 rib assemblies are bonded with skin of the torque shaft. Before bonding of this rib assemblies, the silicon rubber tubular bag are positioned at the correct location. After skin lay up, whole part is transferred to the matched die composite bottom mould. The horn location is maintained at required position using spindle as ref, by providing split moulds with horn bolting arrangement. This horn bolting is essential, because actuator attachment angle 12.1º need to be maintained with any deviation. The top mould is closed with bottom mould using mould clamps. Since silicon rubber tubular bag are used with nipples, it is required to take extreme care during vacuum bagging. So that it should withstand the autoclave pressure and temperature .

The part is cured under full vacuum and 7 bar external pressure at 176°C as per 914C cure cycle system . Post curing of torque shaft is carried out by keeping in free standing position. The component after post curing is shown in Fig-2.

6.QUALITY ASSURANCE

The lay up stage is constantly monitored and certified by the QA personnel. The cure cycle is recorded and certified. The traveller coupon is subjected to destructive tests like ILSS, Flexure etc,. to qualify the curing process. The component is subjected to dimensional checks and accepted. The component is ‘C’ scanned , and no gross defects were noticed. Leading edge portions are manually inspected using ultrasound pulse-echo method.(Ultrasonic flaw detector sonic- 138P). The thickness also measured using the same equipment is conformed the uniform degree of component consolidation and measured thickness correlated with the drawing thickness.

7. QUALIFICATION TEST

The aim of the qualification test is to validate the mathematical modeling and to gain confidence in design and manufacturing process. Under the developmental test the torque shaft have been subjected to static and fatigue test. Static test is to assess the strength and stiffness parameters of the torque shaft under the application of tension & compression load [3]. Simulation of loads and support conditions are two important inputs while deflections and strains are two important outputs in the testing. The torque shaft failed at a load of 5373 kgs. and the corresponding maximum strain level was 4770 micro strain, and the deflection was 8.09mm. The fatigue testing was carried out with in the load limit of 4000 Kgs, strains were monitored for every 5000 cycles. It withstood 2,11,305 cycles without any failure.

8. CONCLUSION

The use of autoclave moulding technology to manufacture the composite torque shaft containing metallic inserts & spindle was proven feasible. This development program has produced valuable data for designing similar drive shafts in the future. The conversion of the titanium torque shaft to composite torque shaft has saved 30% cost and 20% process time. It is found that with effective tool design, any complicated component can be fabricated using composite material. This part development is a best evident that how the improvements in design and fabrication methods will bring cost savings in the aircraft industries.

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