



Aerospace Composite Solutions

DISCUSSING HOW COMPOSITES ARE PROVEN TO BE THE OPTIMUM METHOD OF PRODUCING THERMOPLASTIC ROTARY-WING DRIVE SHAFTS, WHILE MEETING ALL THE OPERATIONAL SPECIFICATIONS OF THE METAL OPTION



WHITEPAPER



Trelleborg Sealing Solutions Aerospace

As a global market leader, Trelleborg Sealing Solutions Aerospace has over 60 years' experience in the industry. Renowned for its huge portfolio of sealing solutions and services for critical hydraulic and engine applications on all types of aircraft, Trelleborg Sealing Solutions Aerospace also offers a wide range of other products. This includes composites and solutions for airframe sealing, EMI, interiors, galleys, oxygen and environmental control systems, as well as for ground support fuel management, de-icing and aircraft jacking equipment.

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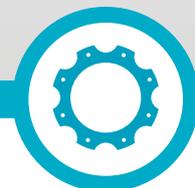
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Introduction

As manufacturers focus on the development of next generation helicopters, they are looking to new technology, materials, and designs to meet their aim for a helicopter that is faster with a longer range and better payload. They also want greater reliability, easier maintenance and operation, lower operating costs, and a reduced logistical footprint. Advanced composite materials are essential for the light weighting needed to achieve these goals.

One key application is the rotary-wing drive shaft that transmits power between the aircraft's engine and tail rotor. Typically, the drive shaft

is made of a multi-segmented metallic system, which is prone to corrosion. An alternative is to make the drive shaft of composites. However, it is essential that the composite solution can meet all operational specifications as the metal option, including ballistic impact survivability.

Research and development was undertaken by Trelleborg Sealing Solutions to prove the optimum method of production of a thermoplastic driveshaft. A case story illustrates the success to the composite alternative to metal driveshafts.

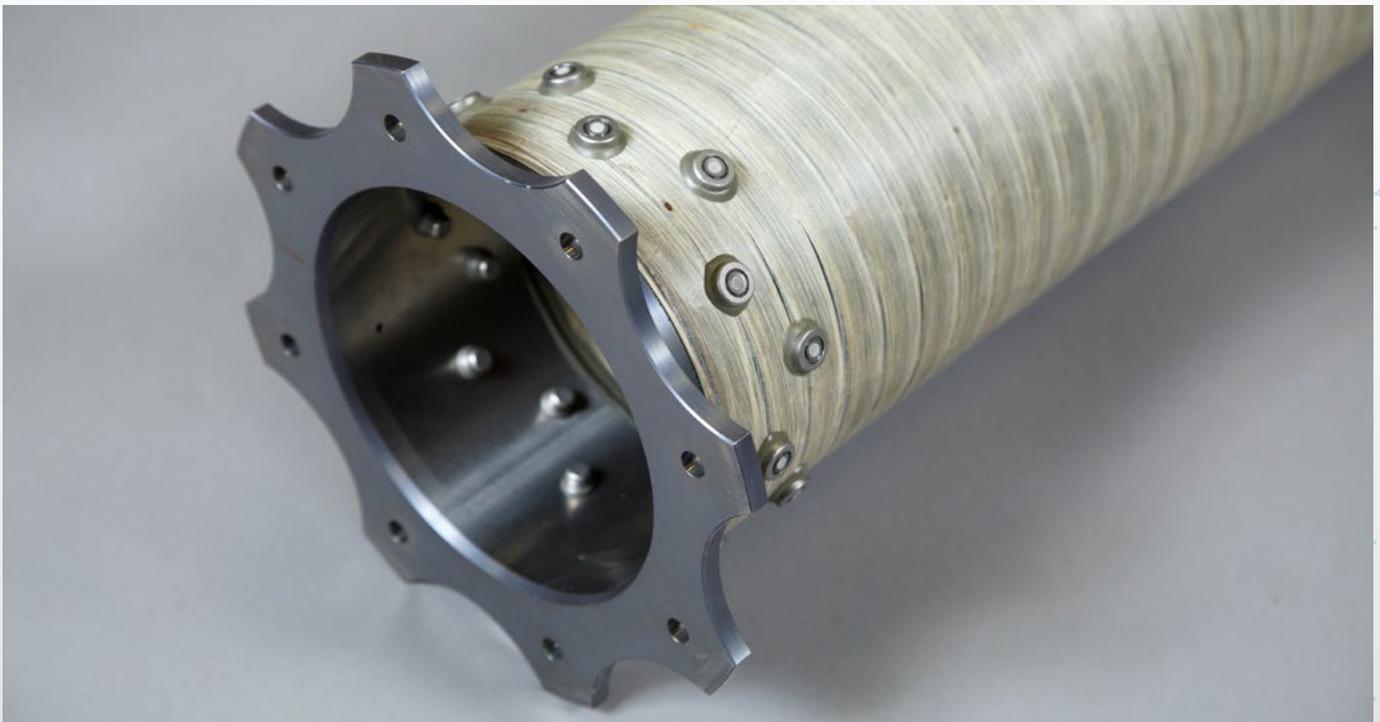
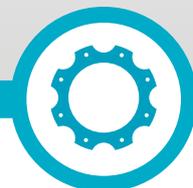


Figure 1: Complete thermoplastic driveshaft with metal coupling

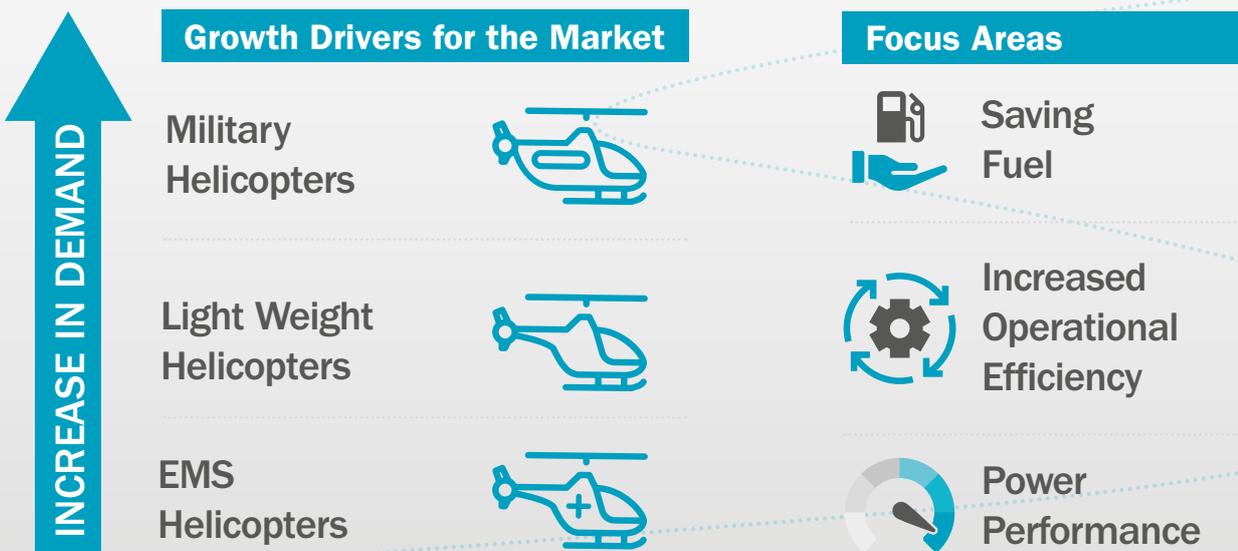


Market

According to Markets and Markets, the global helicopter market size is projected to grow from 21.3 billion USD in 2020 to 36.9 billion USD by 2025; a compound annual growth rate (CAGR) of 11.7%. Increased demand for military, light weight, and emergency medical services (EMS) helicopters are significant growth drivers for the market.

Saving fuel and operational efficiency are the prime focus areas, as well improved helicopter power performance. Manufacturers have undertaken efforts to reduce the overall weight of helicopter engines to help lower fuel consumption and enhance cost-effectiveness through technological advancements.

Helicopter Market Size



Advanced composites for vertical lift

The value of weight saved in vertical lift is 10 times that of a fixed wing aircraft and 100 times that of ground transportation; so light weighting is essential in vertical lift aircraft and composite materials have been used for this purpose in rotorcraft for decades.

The US Army's Advanced Composite Airframe Program (ACAP) in 1981 was the first significant application of composite materials in a helicopter. This was a project to develop an all-composite helicopter fuselage, considerably lighter and less costly to build than predominantly metal airframes. Contracts were awarded to Sikorsky and Bell who developed the S-75 and D-292

experimental helicopters that flew in the mid-1980s. Both of these prototypes exceeded the design requirements and the technology developed lead to the extensive use of composites in all subsequent rotorcraft.

The early designs were "black aluminum", meaning that the composite was treated like an isotropic metal. Fiberglass and carbon fiber fabrics were packed by hand into molds, smeared with epoxy resin, and cured in an autoclave. This process did not take advantage of the directional strength of composite fibers, was labor intensive, error prone, time consuming, and energy intensive.



Figure 2: First composite helicopters, Sikorsky S-75, and Bell D-292 – first flights in the mid-1980s



Modern aerospace composite manufacturing uses Automated Fiber Placement (AFP) to place pre-impregnated unidirectional composite tapes in the directions needed for maximum strength and stiffness. Epoxy resins have been replaced by toughened epoxy for improved damage tolerance and the current state of the art is Out of Autoclave (OoA). This is where thermoset composites are vacuum bagged, and oven-cured.

Alternatively, thermoplastic composites are In-Situ Consolidated (ISC), which involves

consolidating the thermoplastic composite prepreg tape in-process as in Additive Manufacturing (AM) so that no autoclave or other post process is needed.

One of the most challenging applications has been dynamic components, including the transmission drive shafts of rotorcraft. The development of composites with high levels of damage tolerance coupled with unique manufacturing processes has made their application to driveshafts a reality.

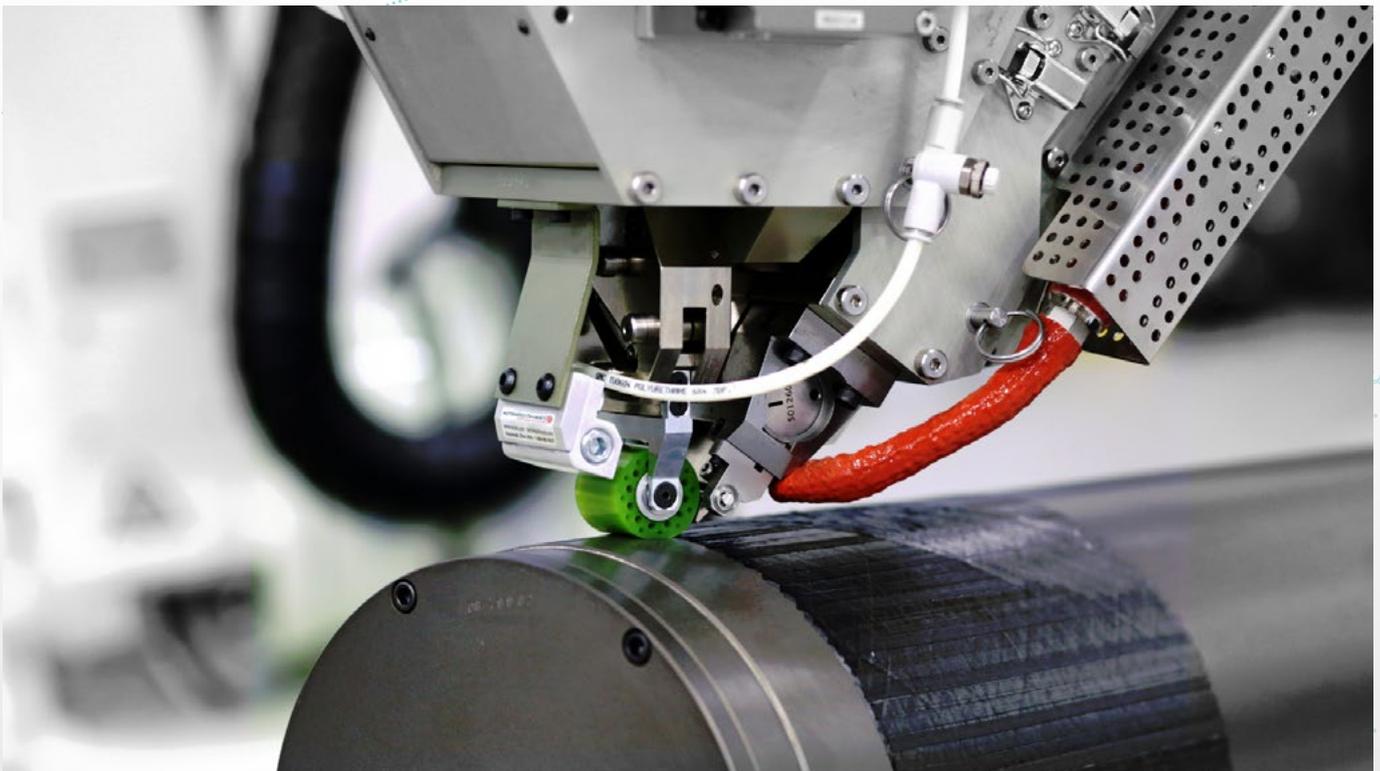


Figure 3: Four tow thermoset processing head



Composite driveshafts

In the early “black aluminum” designs, weight savings in the composite driveshaft were due mostly to their lower density compared to aluminum. As driveshafts primarily transmit torque, placing the reinforcing fibers at ± 45 -degree angle provides maximum torque transfer and weight savings. Other factors for consideration are lateral stiffness (natural frequency), coefficient of thermal expansion (CTE), and ballistic impact.

One of the many advantages of composites is that fiber type and architecture can be designed to optimize a driveshaft for a given

application. For example, a modern helicopter with a composite tail boom should have a composite tail rotor driveshaft to match CTE. Aluminum has a much higher CTE than carbon fiber composites ($\sim 24 \mu\text{m}/\text{m}\cdot^\circ\text{C}$ vs. $\sim 0 \mu\text{m}/\text{m}\cdot^\circ\text{C}$) so the length difference must be corrected with expensive flexible couplings. Orienting fibers along the length (0°) of the driveshaft results in lower CTE and higher lateral stiffness, allowing fewer couplings and longer shafts to save weight and cost.

Thermoset composite driveshafts

Braided or filament wound thermoset helicopter driveshafts have been developed to demonstrate the above advantages. Both processes have limits on fiber angles and the fibers are interwoven resulting in undulations that reduce strength and stiffness. More importantly, thermoset composites always have a bulk factor which needs to be compressed out during post process consolidation. In the case of a closed section like a driveshaft this means that the fibers will wrinkle and lose strength during consolidation.

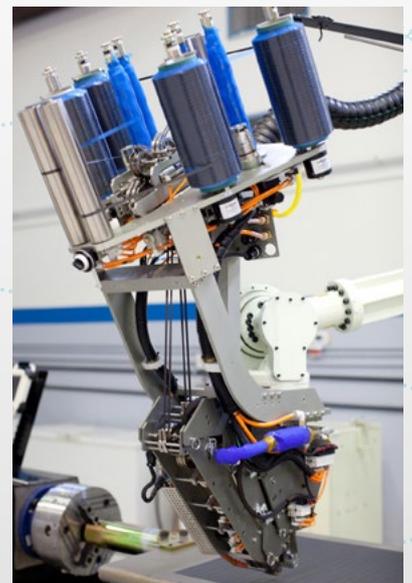


Figure 4: Four tow thermoset processing head showing the material creel



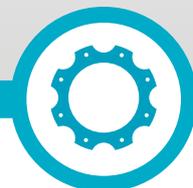
Thermoplastic composites driveshafts

Thermoplastics being lighter weight with high damage tolerance, outstanding fatigue life, and dampening properties, make them ideal for driveshafts. In addition, as manufacturing

can utilize ISC technology, they provide further benefits of no fiber wrinkling, unlimited choice of fiber angles and no post processes.

Overview of advantages of thermoplastic Composites

- Extreme toughness, damage tolerance and survivability
- Outstanding energy absorption with the highest specific energy absorption of any material
- More than twice the fatigue resistance of toughened epoxy under the Elevated Temperature Wet (ETW) testing criteria
- Rapid processing capabilities for stamping, pressing, bending and thermal bonding, for instance
- Recyclable and re-processable
- Improved damping with low NHV (Noise, Harshness, Vibration)
- Superior environmental, chemical, and solvent resistance
- Excellent wear resistance
- Low coefficient of friction
- Low water absorption, dependent on polymer
- Stable glass temperature transition temperature (T_g) even under hot and wet conditions
- FST (Fire, Smoke, Toxicity) stability, dependent on polymer
- No refrigeration, out-time and exotherm considerations
- Melt processable so no cure chemistry or long soak times
- Minimal toxicity and hazardous chemical issues compared to thermosets



Proving composites in application

Trelleborg Sealing Solutions undertook research and development to prove thermoplastic composites in the driveshaft application as well as to establish the optimum ply configuration. The results of this investigation are detailed below.

Ply configuration

Based upon previous damage-tolerant driveshaft designs using an Carbon Fiber/PEEK material system, it was found that ply configurations, which normally carry the torsional loads most efficiently (i.e., large fraction of $\pm 45^\circ$ [0.79 radians] plies), are not very damage tolerant. These plies were observed to be poor at the redistribution of the stress concentrations around a damaged area.

The shafts that produced the greatest post damage residual torsion capability with impact edge damage at a 45° angle (0.79 radians), were those with no fibers oriented near $\pm 45^\circ$ (0.79 radians), but with a large fraction of plies at a low angle (from $\pm 17^\circ$ [0.3 radians] to $\pm 22.5^\circ$ [0.39 radians]), with the balance at a very high angle approaching 90° (1.57 radians). This high angle assists in strengthening the shaft against buckling failures.

Although the design focus was on this low-angle approach, excursions were performed

with configurations that use more traditional ply orientations to evaluate the effectiveness of this principle. For all orientations evaluated, a balance and symmetry were maintained within the layup to the extent possible.

The design weight was used as a limiting factor to define the number of plies used in the design of the shafts based on the driveshaft being at least 15% less than an aluminum shaft.

From numerous drive-shaft designs and their respective analyses, it was concluded that the optimum ply orientation involved predominately low-angle fibers between 22° (0.38 radians) and 25° (0.44 radians), with additional fibers placed as near to 90° (1.57 radians) as possible (78.5° [1.37 radians] to 88.5° [1.54 radians]). The optimum ratio of low- to high-angle fibers was approximately 70/30.

Additionally, it was found that the introduction of 0° (0 radians) plies and 45° (0.79 radians) plies in place of the near 90° (1.57 radians) and low-angle plies tended to significantly decrease the post damage properties of the shafts, although the use of 0° (0 radians) plies as a replacement for the low-angle plies could alter shaft frequency through the increase of shaft lateral stiffness.



With an open gouge for the shaft produced by an impact event, the primary mode of failure is buckling. Neither 0° (0 radians) nor 45° (0.79 radians) plies do much, if anything, to resist a buckling failure. This observation was supported when comparing the shaft buckling torque in the undamaged state to the post damage torque. From this comparison, it was apparent that the greater the buckling torsion, the higher the post damage torsion capability.

Based on the results of the analysis, four shaft configurations were selected for impact testing, which included two thicknesses and orientations, all of which exhibited weight reductions over equivalent aluminum shafts of over 30%. They were designated as configurations A, B, C, and D, and are provided with their respective calculated properties in Table 1. Figure 6 shows a shaft section fabricated to support the design verification tests.

Test Config.	Ply Count	Shaft Laminate Makeup (Balanced and Symmetric)		Maximum Torque, Undamaged, in.-lb.(N · m)	Maximum Torque, damaged, in.-lb.(N · m)	Buckling Torque, Undamaged, in.-lb.(N · m)	Shaft Weight, lb _m /in. (kg/m)
		Orientations, degrees (radians)	Percent Breakout				
A	44	±88.5/±22 (±1.54/±0.38)	45/55	258,500 (29,207)	49,200 (5,559)	292,572 (33,056)	0.2006 (3.5823)
B	44	±88.5/±28 (±1.54/±0.49)	45/55	287,800 (32,517)	53,200 (6,011)	269,072 (30,401)	0.2006 (3.5823)
C	36	±88.5/±22 (±1.54/±0.38)	33.5/66.5	197,600 (22,326)	41,700 (4,711)	200,341 (22,636)	0.1629 (2.9091)
D	36	±78.5/±25 (±1.37/±0.44)	33.5/66.5	229,100 (25,885)	44,300 (5,005)	182,202 (20,586)	0.1629 (2.9091)

Table 1: Select configuration for test and their calculated properties

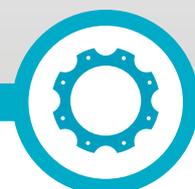




Figure 6: A typical Carbon Fiber/PEEK composite drive shaft processed with the in-situ tape placement process

In-situ tape-placement fabrication process

The successful application of the Carbon Fiber/PEEK material to a drive shaft requires accurate fiber placement, minimal opportunity for fiber wrinkling, controlled resin flow, and dimensional stability throughout the fabrication process. An in-situ tape-placement fabrication process developed specifically for the material system satisfactorily achieved these requirements.

In the in-situ or “on-the-fly” processing, the part is fully consolidated as the raw material is being put into place. Unlike typical autoclave processes, there are no intermediate debulking steps or post processing needed.

The raw material is first heated using a hot nitrogen gas torch stream, which is heated as it passes through an electrically resistive



Figure 7: Driveshaft fabrication using in-situ AFP process

heating element, to elevate the raw material temperature up to its melting point. The material is then passed between a rigid steel roller and the processing tool to consolidate the material as illustrated in Figure 7.

The first layer of material is placed onto a cold tool. Subsequent layers are placed on top of and melt-bonded to the previous layers to form the laminate of desired thickness and fiber orientation. The laminate is built to the desired specifications, removed from the tooling, and is considered complete. There is no post processing needed. The part is then trimmed to the desired geometry and is ready for use.



Continuous, unidirectional, graphite fiber-reinforced PEEK thermoplastic is ideally suited for this process. The raw material is delivered as a prepreg tape, meaning that the raw fibers are pre-impregnated with the thermoplastic resin. This is done offline at the material supplier's facility. Because the material is a thermoplastic, there is no shelf life and no "out time" issues. The raw material can be stored at room temperature indefinitely. This characteristic is different from that of thermoset materials, which require relatively strict storage temperatures and have a limited shelf life.

This process has exact inner diameter control to the composite shaft and prevents the wrinkling of fibers due to the compaction process. The unique nature of the material supports this sequential layering process through the resin chemistry, which through the application of localized heat and pressure fuses individual layers together forming the laminate (i.e., original additive manufacturing). The process and results are not easily, if at all, achieved with other systems.

Properties provided by the Carbon Fiber/PEEK material system and in-situ tape process

- Exact inner diameter control of the shaft tube
- Frequency-tailorable structure
- Fiber orientations from 0° to 90° (0 to 1.57 radians)
- Superior impact tolerance
- Excellent environmental and fluid resistance
- High level of damage tolerance and durability
- Reduced weight over metal and most composite counterparts
- Machinability superior to most composites
- Lower overall cost due to elimination of secondary curing operations
- Length and thickness independence that is restricted only by the fabrication envelope



Test procedure

The impact and static torsion properties of the composite drive shaft were validated through a series of tests.

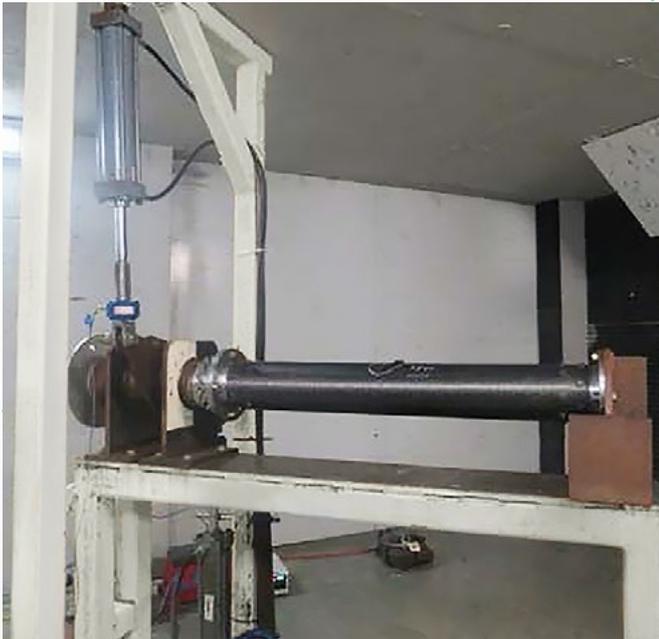


Figure 8: Test stand with drive shaft

The fixture in Figure 8 used applied torsion through a rotation disc via actuators, with a digital inclinometer used to support measurement of shaft rotational angular deflection. It incorporated an actuator system to apply and maintain a predefined torsion load during test and to increase loading at a 20,000 in.-lb_r/min (2,260 N·m/min) rate after damage until the test shaft failed.

Throughout the load application, the angular deflection of the shaft was measured. A plot was generated comparing reacted torque as a

function of angular deflection to characterize the performance of the shaft.

Both normal and tumbled projectile events were used to damage the test shafts. Figures 9 and 10 show typical damage for each event type although the degree of damage varied for the test events.



Figure 9: Test result for normal impact event

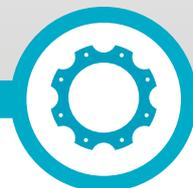
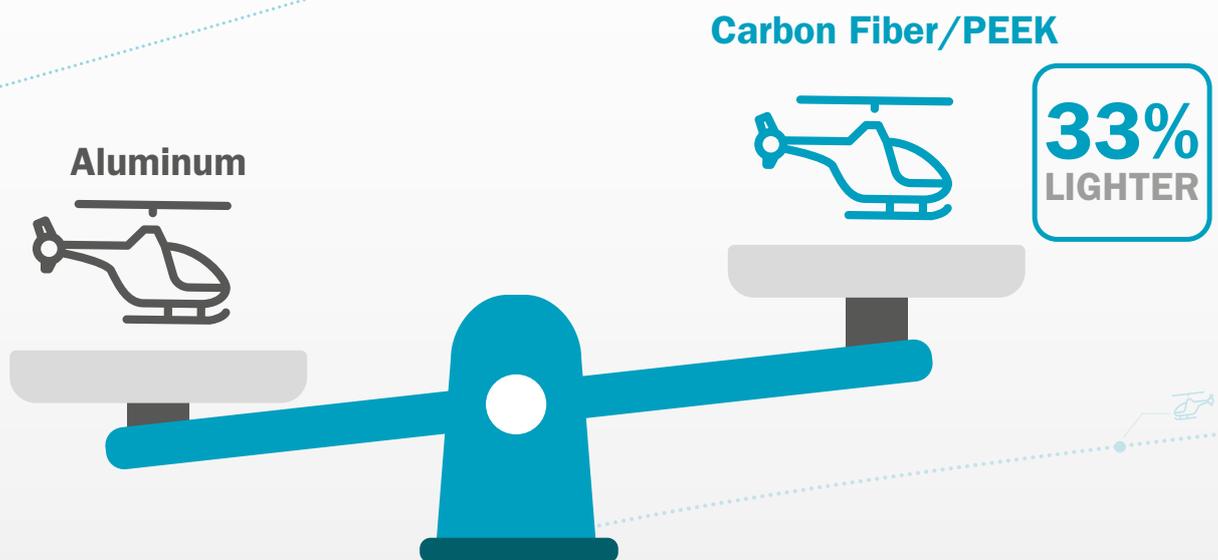


Figure 10: Test results for a tumbled impact event



Conclusions from tests

1. The potential of an Carbon Fiber/PEEK damage-tolerant drive shaft for application to a helicopter drive train was proved.
2. A conservative design methodology was demonstrated to be capable of supporting the design of lightweight, damage-tolerant, highly survivable composite drive shafts that use Carbon Fiber/PEEK.
3. Using Carbon Fiber/PEEK, it is possible to develop helicopter drive-shaft designs that can produce weight savings over the aluminum tubes by up to 33%.
4. In each of the developed designs, the measured properties of the test drive shafts were greater than that calculated in the design process.



Case Study – Thermoplastic Composite Driveshaft for the CH-53K

Trelleborg Sealing Solutions was awarded a contract with NAVAIR in 2010 titled “*Innovative Material Design and Manufacturing Development for a Lightweight, Low Cost, Highly Survivable Drive Shaft*”. The goal was to develop a leap-step improved driveshaft for the CH-53K helicopter using advanced thermoplastic composite materials and the ISC process.

The Sikorsky CH-53K King Stallion is Sikorsky’s latest version of their heavy-lift cargo helicopter developed for the US DoD. Its 22,500 HP (16,800 kW) power and composite intensive

design provide greater speed and nearly double the payload.

Figure 11 shows the drivetrain featuring six driveshafts and a pylon shaft that were previously made of aluminum.

Survive Engineering was contracted to design the driveshaft to meet all operational specifications including ballistic impact survivability. They used LS-Dyna FEA simulation to model the ballistic damage and developed composite layup designs.

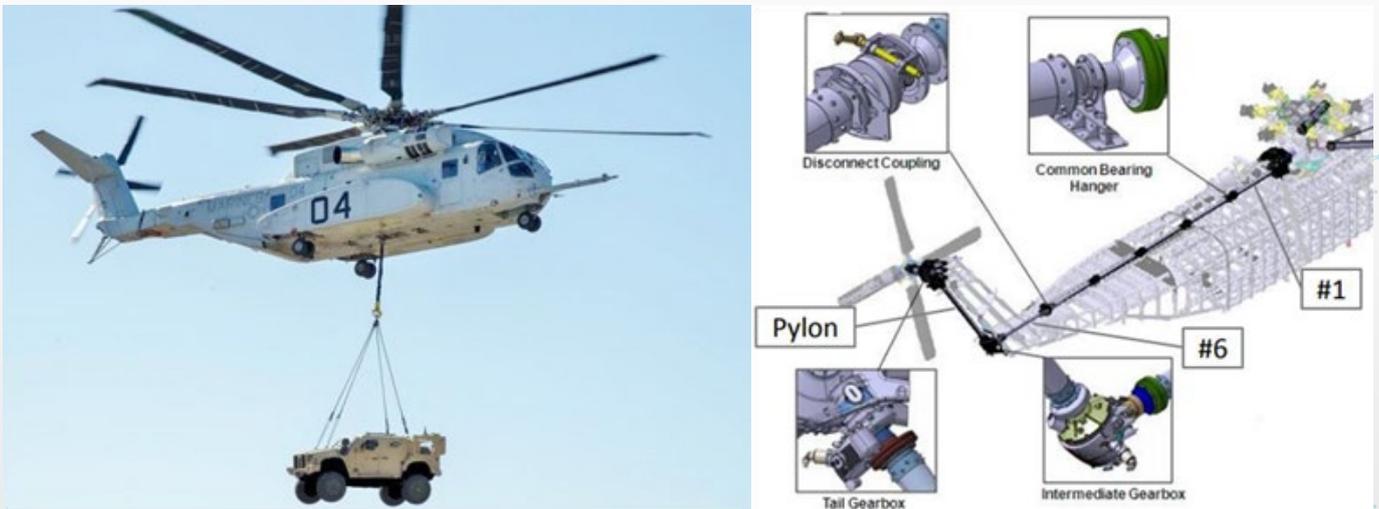


Figure 11: CH-53K King Stallion heavy lift helicopter and tail rotor drivetrain



Figure 12 illustrates the results of this FEA simulation comparing thermoplastic (PEEK) composite to aerospace grade toughened epoxy composites (8552) for different driveshaft designs.

To verify the analysis, Trelleborg Sealing solutions fabricated driveshafts with differing. The ISC process is illustrated in Figure 13 with a schematic diagram and driveshaft during fabrication in an ISC robotic work cell.

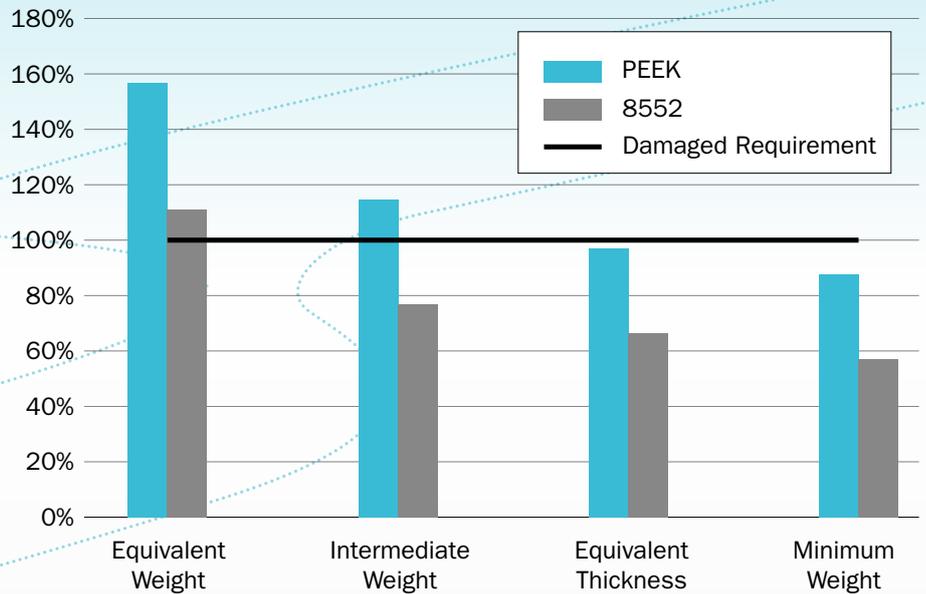


Figure 12: Thermoplastic composite (PEEK) vs toughened epoxy (8552) ballistic damage tolerance 5

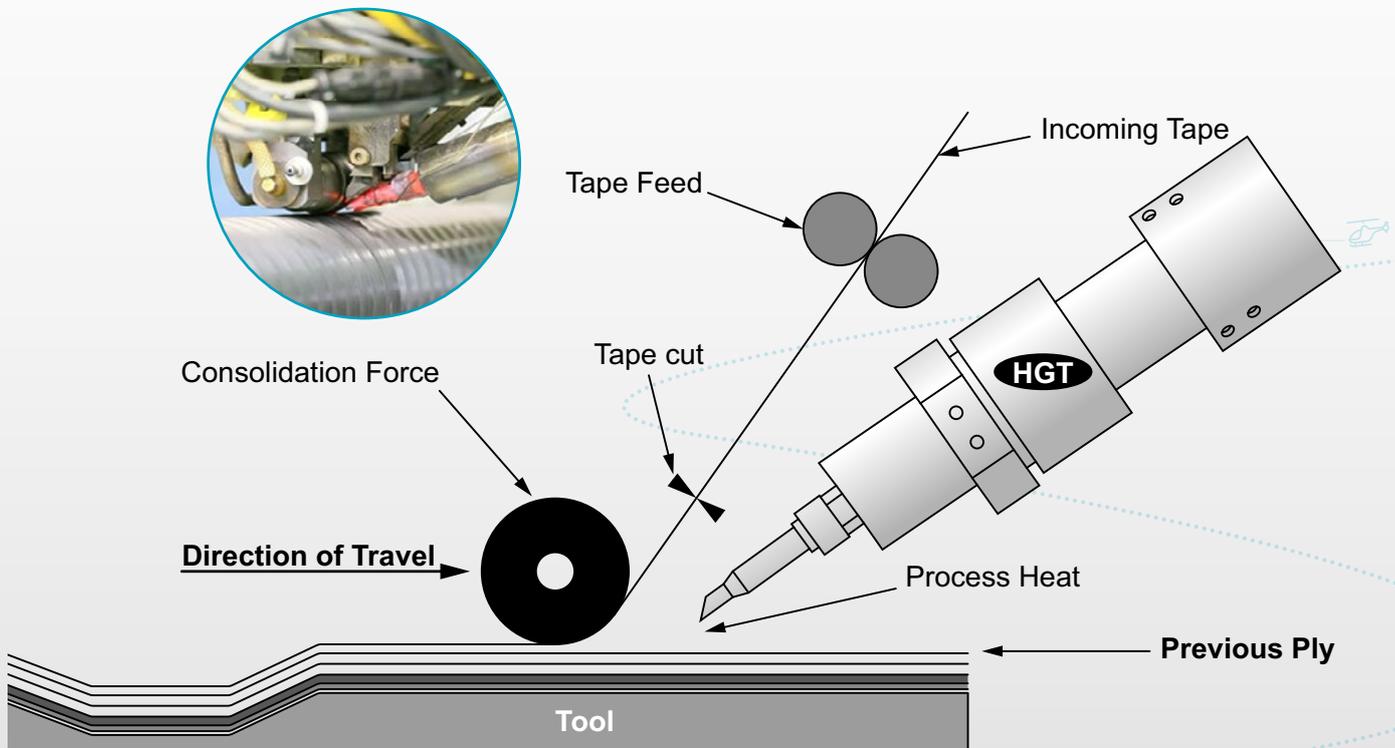
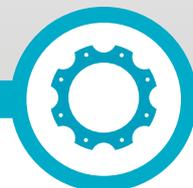


Figure 13: The ISC process



The prototype driveshafts were then ballistically impacted with a large caliber round in the worst

possible 45° glancing angle and then torque tested to failure.

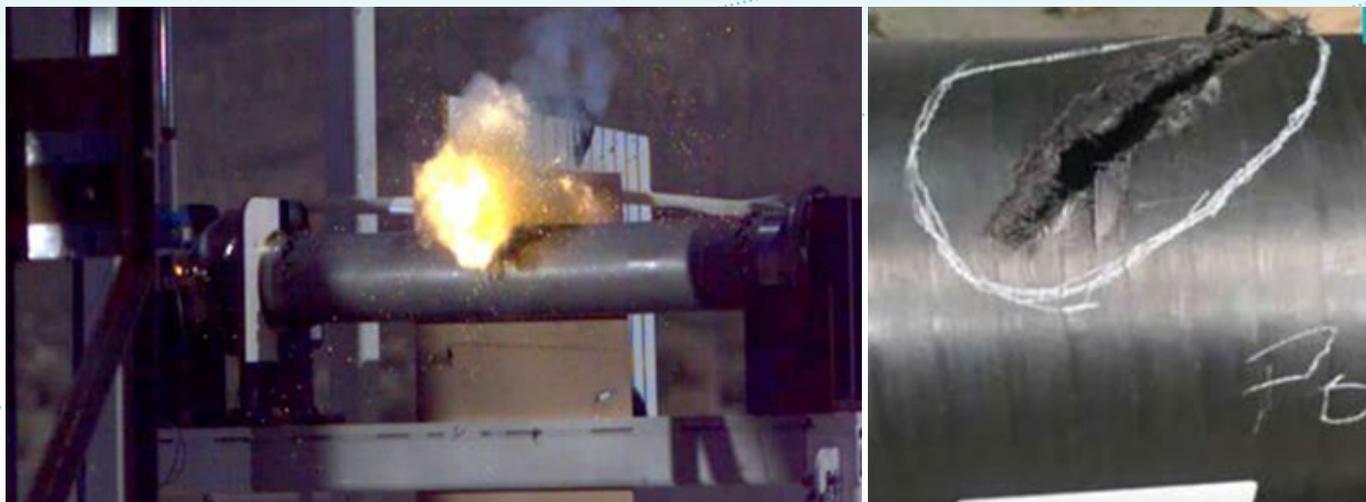
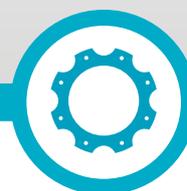


Figure 14: Ballistic testing driveshafts



The ballistic test results are illustrated in Figure 15. All the driveshafts exceeded design requirements indicating that further optimization could lead to a lower weight design. However, it was decided to go with a design that was 33%

lower weight with 150% improved post ballistic torque retention exceeding the weight reduction goal and greatly increasing survivability in impact.

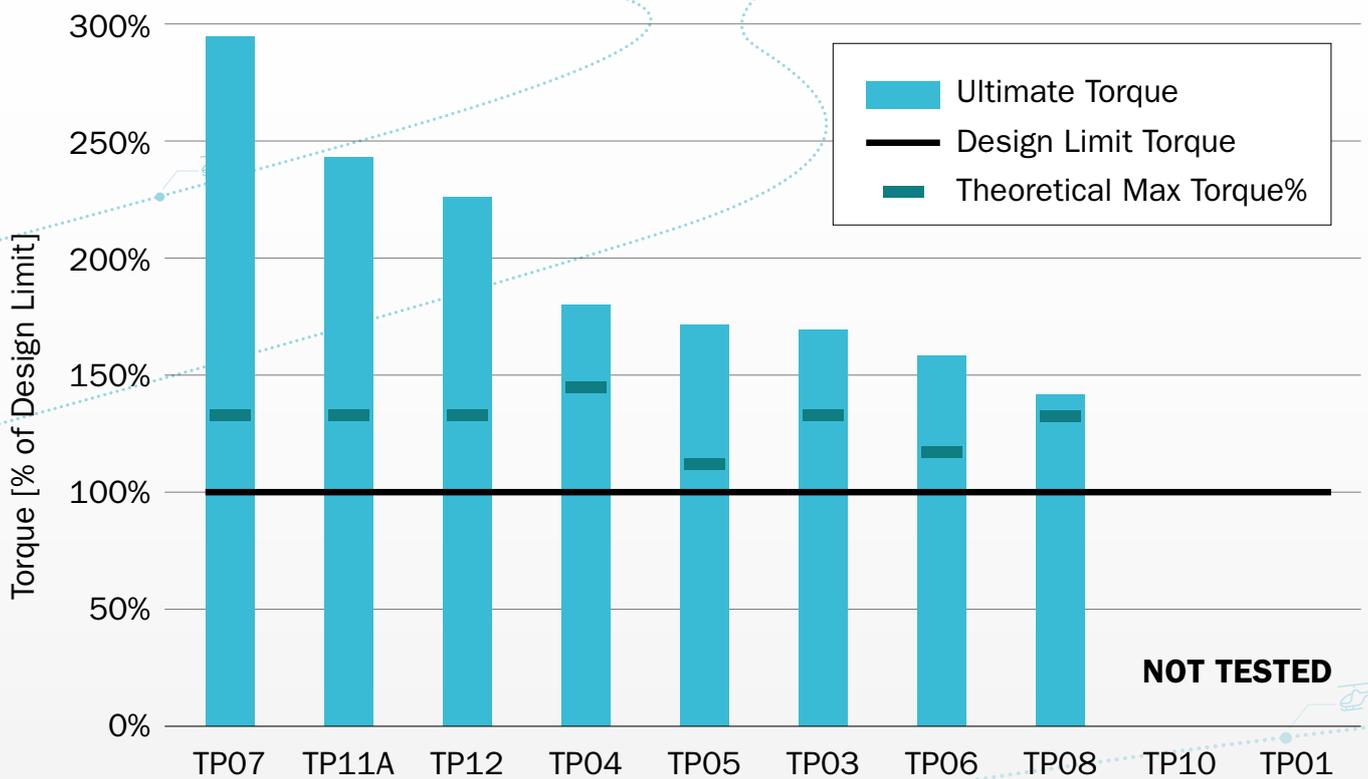


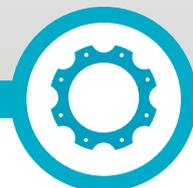
Figure 15: Results of driveshaft ballistic testing for various prototype designs



The final design is shown in Figure 16 with the end fittings attached.



Figure 16: Final driveshaft design fully assembled



Conclusion

The use of composites in rotary-wing aircrafts is an effective way of meeting the helicopter manufacturers' primary objective of lightweighting to lower fuel costs and improve efficiency. One area of focus is the driveshaft. However, it is essential that the composite solution can meet all operational specifications as the original metal option, including ballistic impact survivability.

Thermoplastic composites that are In-Situ Consolidated (ISC) offer significant advantages over other composite methodologies for dynamic components. Their high levels of damage tolerance has made their application to drive shafts a reality.

Trelleborg Sealing Solutions undertook research and development to prove thermoplastic composites in the driveshaft application. The results were overwhelmingly positive, with

them providing superior impact tolerance and durability. In particular, weight savings over aluminum tubes were up to 33%. In addition, the ability to tailor shaft properties for a balanced structural design with shaft frequency was demonstrated through design and ultimate successful operation of a tailored drive shaft in a dynamic environment.

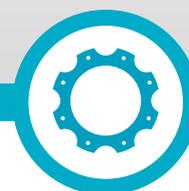
The success of this program and previous research has laid the groundwork for Carbon Fiber/PEEK and its derivatives to be considered in numerous air and ground vehicle applications, both static and dynamic, offering advances in performance at lower weights than offered by traditional materials.

A case study illustrates the application of the composite technology in a real design project involving the driveshaft. This paves the way for future lightweighting of rotary-wing aircraft.



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