DEVELOPMENT OF A WEIGHT-OPTIMIZED SINGLE-PIECE COMPOSITE DRIVE SHAFT FOR TAIL DRIVE LINE APPLICATION

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Abstract

The submitted paper aims to present the development of the components of a mechanical drive line using composite drive shafts with integrated composite flanges for tail drive line of a helicopter from Airbus Helicopters, sponsor of this initiative. This work is part of the RECOMPOSE (aRbrE COMPOSitE) project funded by the European Union NextGeneration EU, the DGAC (French Civil Aviation Authority) and supported by CORAC (Civil Aviation Research Council), from July 2021 to July 2025, and aims to increase the competitiveness of helicopters while reducing their CO2 emissions. Project team was made up of Nexteam group, CT Ingénierie (innovation and engineering services - France) and Arts et Métiers (University - France).

1. NOTATION

Acronyms:

TRL	Technology Readiness Level
TH	Tsai-Hill
YS	Yamada-Sun
BVID	Barely Visible Impact Damage
RH	Relative Humidity

2. INTRODUCTION AND PROBLEMATIC

Developing composite drive shafts is an opportunity to extent mass saving by increasing the bending critical frequencies at their limits if the driveline to remains subcritical. Considering this, there is no need for additional devices like dampers since the vibration levels remain stable and the number of supports can be reduced due to the extended length of the shafts offered by the high modulus properties of the carbon fiber, thus saving carried weight. Otherwise, if the driveline is supercritical, composite drive shafts provide an opportunity to extend their length even more to increase mass saving by reducing supports and coupling numbers at its lowest.

Composite drive shaft is an existing technology since the 20th century which is an evolution of the classical metallic drive shaft. Metallic transmission drive shafts have been upgraded with the use of a carbon fiber tube with two metallic flanges bonded and/or riveted at both terminal ends [Ref. 1 & 2]. This solution offers good benefits in terms of mass saving, since metallic density is replaced by composite density approximatively 2 to 5 times lighter. But this configuration adds manufacturing complications to ensure the expected quality of the drive shaft (roundness, coaxiality, cylindricity, run-out), and the expected lifetime of the connection between the metallic flange and the composite tube may vary sharply which is hard to size properly and results in an oversized part to prevent any precocious failure. An example of the current solution used in the industry is illustrated on the figure

1, with the top two images [Ref. 11 & 12], and the two lower images are the solution under development within RECOMPOSE project.

Figure 1: Comparison of an integrated metallic flange (top two images) and a fully composite flange (bottom two images)

Mass saving can be further increased by replacing metallic flanges by integrated composites ones, meaning that the drive shaft is a single-piece composite part. This solution offers multiple advantages since the number of manufacturing and assembly operations is greatly decreased, offering viable economical outlooks. Composite technology relies heavily on manual operations enabling automation of manufacturing and assembly processes as a key to the success of the technology. Fully composite drive shaft has very few occurrences in the literature, for example within patent for the manufacturing of the flanges [Ref. 6 & 7]. An example of integrated flange has been demonstrated in [Ref. 3] on a concept of pipe with flanges made of continuous fibre-reinforced composite, but these parts are not loaded in the same way as drive shafts are, respectively in bending, tension and extension then mainly in torsion. Papers and documents available in the literature doesn't present a sizing method associated with specifications associated to the product.

The technical lock-up identified is the capability of designing a fully composite drive shaft based on specifications, with optimized mass and frequency positioning, while the technological lock-up this work aims to provide advances is the capability to manufacture such a composite drive shaft. This offers room for improvement in both engineering design and manufacturing of optimized composite products.

3. DESIGN STRATEGY OF FULLY COMPOSITE DRIVE SHAFT

Most papers in the literature focus on the design and the optimization of the tube subject to torsional loading. There is a lack of design methodology for fully composite drive shafts in accordance with a specific manufacturing process, mainly because integrated composite flange doesn't reach a TRL such as it is integrated in aircraft. In particular, areas such as fixation holes, fillet radius between the tube and the face of the flange need specific design methods. There is also a need to consider these design methods regarding the specific manufacturing process used to obtain the drive shaft, because composite final properties are highly dependent on the manufacturing process.

Current design methods used by major aeronautics companies [Ref. 4] rely on some assumptions that constrains the manufacturing process and can't always be matched. For example, there are rules about the stacking repartition of the different main angles (0°, -45°, 45° and 90°) and additional free angle value that need to be satisfied with a percentage by each angle. Rule about a minimal number of plies for each angle is also a design assumption from these methods, with a repartition of at least 8% of the plies in each of the main directions [Ref. 4, 8, 9, 10]. These constraints prevent a lot of products to exist because it would remove the gains from the composite material, like weight saving, by respecting most of the design rules. This composite drive shaft development doesn't take into account all these constraints to design a new and innovative product.

One of the objectives of this work is to explore the engineering and manufacturing sustainability of unconventional composite definition applied to composite transmission drive shafts. The exploration of the design solution space is motivated by the development of a manufacturing process with a high potential of automation but constraining the definition of the stacking sequence of the drive shaft.

The approach to develop this technology follows the classical TRL in parallel with the test pyramid, Figure 2. This approach helps in structuring the testing process in a way that maximizes efficiency and effectiveness while minimizing costs and time thanks to a progressive increase of product definition. In this context of composite drive shaft development, the test pyramid consists of four levels:

- Coupon Tests (Unitary Tests) are the most fundamental and granular level of tests. They involve testing very simple standardized specimens, often referred to as "coupons," to characterize the mechanical properties of the composite material within a standardized framework. This level helps to obtain baseline data on material properties such as strength, stiffness, and durability. It also gives insight into understanding the basic behavior of the composite material and ensures it meets the required standards before proceeding to more complex tests.
- Shortened Shaft Tests are conducted on shortened versions of the actual shaft. These tests focus on analyzing and correlating the behavior and properties of the components or a part of it, such as the composite flange. This provides insights into component-specific issues and performance, allowing for adjustments and improvements before full-scale testing.
- Full Shaft Tests in Laboratory Conditions involves testing the complete shaft assembly under controlled laboratory conditions. The goal is to ensure that the final product definition meets all specified requirements. These tests aim to confirm the overall integrity and functionality of the shaft, ensuring it is ready for real-world application.

Real Operating Environment Tests are the final level involves testing the product in its actual operating environment. This real-world experimentation is critical to validate the product's performance under actual usage conditions ensuring it meets end-user requirements.

To ensure that technology maturity increase with these tests, correlation is performed at every level between numerical model (or any other engineering model) and experimental results. At this stage, designers capture the essential knowledge for the development of the product, including the confidence in the current engineering methods and models, but also define the outlook of improvement considering the unmet specifications.

3.1. Coupon level

Following this test pyramid strategy to develop the fully composite drive shaft, the first tests on coupon have been performed to capture the mechanical properties of the composite material used to build the shaft, Figure 3. These tests have led to the identification of mechanical properties along the main directions of the composite material by means of tensile and compression tests along fiber (0°) and matrix directions (90°). Measured properties are Young's Modulus along the main direction, the ultimate strength and Poisson's ratios. In-plane shear tests have also been performed to complete core data needed for an orthotropic modeling, but also traction tests within a high temperature environment to assess the loss of mechanical properties of the fiber in hot environment, alike operating conditions. A summary of the experiments is presented in the table below

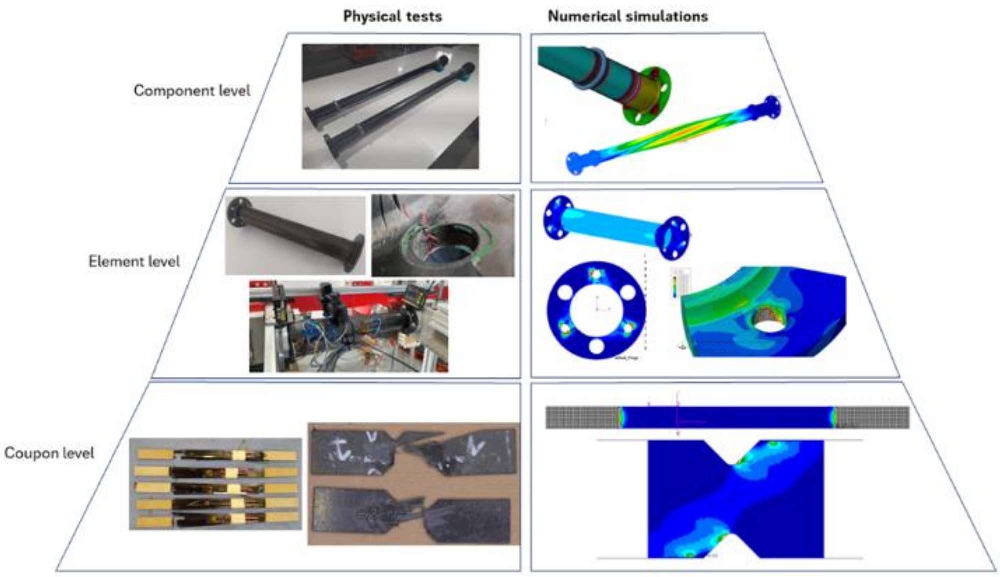

Figure 2: Test pyramid approach used within RECOMPOSE project

Table 1: Difference between numerical and experimental results mechanical properties.

Loading	Fiber direction	Standard	Difference between numerical and experimental results
Tension	**0°**	**ASTM D3039**	**-3.0 %**
Tension	**90°**	**ASTM D3039**	**5.5 %**
Compression	**0°**	**ASTM D6641**	**2.3 %**
Compression	**90°**	**ASTM D6641**	**-4.8 %**
Shear (in plane)	**Nonstandard**	**ASTM D7078**	**-7.6 %**
Shear (in plane)	**Nonstandard**	**ASTM D7078**	**-4.6 %**
Shear (in plane)	**+/- 45°**	**ASTM D3518**	**0.5 %**

These experimental results are to be recaptured by numerical simulations in order to ensure that the mechanical behavior of the composite part is correctly represented by numerical models. All models are realized and post-processed with Patran 2019 software, and the computation is made through Nastran 2013 software. CQUAD4 elements are used to mesh the coupon specimen models, and PCOMP properties are used to apply the stacking sequence of the composite laminate made from MAT8 material definition (corresponding to an in-plane orthotropic material).

The results of the very first step of the test pyramid are as follows: elastic properties match well between experimental and numerical results with at most 6% of deviation for tension and compression results and up to 8% of deviation in shear. In the first case, Young's Modulus in tension slightly differs from the one in compression, leading to a discrepancy between the modulus obtained from the tests and the one averaged used in numerical simulations. For shear considerations, the deviation is explained by the standard used: the shear property is measured by a tensile test of a +/-45° stacking, which results in a non-pure shear stress, resulting in an acceptable level of divergence between numerical model and experimental results. However, failure levels of each coupon specimen are harder to capture in numerical models. As it is presented in the table 1, max stress criterion is a good failure indicator for the loading along the fiber direction and for 90° compression, but discrepancies appear in 90° tension and every shear model. The use of a combined failure criterion like Tsai-Hill (TH), which is the most popular failure criterion for composite applications, worsen the failure stress prediction. This can be explained by the local stress concentration caused by the geometry and/or the pressure applied by the grip. This pressure is not measured during the tests and can influence the allowable strength of the material. Lack of method have been found missing to get a comprehensive capture of the mechanical failure of the composite part on standard specimens.

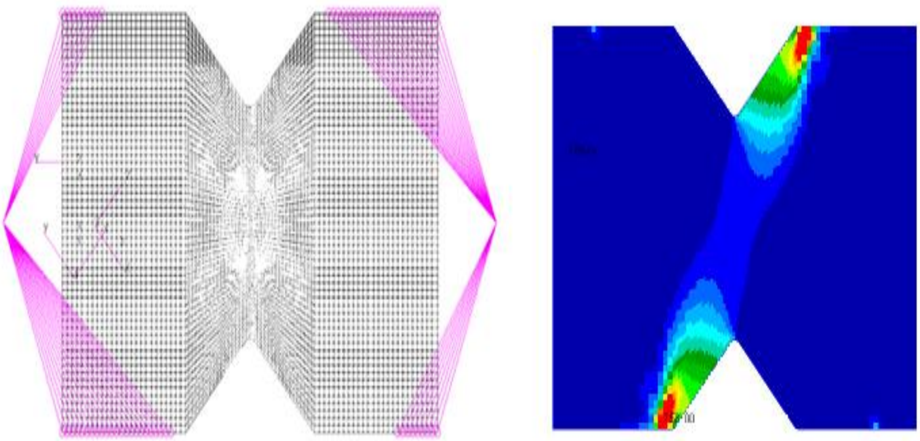

Figure 3: Example of shear coupon specimen mesh and stress results with Patran software

Table 2: Coupon specimens failure criteria numerical results

Loading	Fiber direction	Standard	Max stress	Tsai-Hill
Tension	**0°**	**ASTM D3039**	**1.04**	**1.26**
Tension	**90°**	**ASTM D3039**	**1.73**	**3.00**
Compression	**0°**	**ASTM D6641**	**1.02**	**1.86**
Compression	**90°**	**ASTM D6641**	**1.01**	**1.01**
Shear (in plane)	**Not standard**	**ASTM D7078**	**6.53**	**45.85**
Shear (in plane)	**Not standard**	**ASTM D7078**	**3.61**	**15.53**
Shear (in plane)	**+/- 45°**	**ASTM D3518**	**0.70**	**0.84**

This table demonstrates the good correlation between first ply failure with max stress criterion of main direction properties. Tsai-Hill, but also other failure criteria like Yamada-Sun (YS) or Hashin are giving slightly conservative results. In the case of shear tests, failure levels are not properly predicted by numerical models. In the case of +/- 45° specimen, failure level is underestimated while for the analysis of a specific angle stacking sequence both max stress and TH highly outlying from the target value. The failure level prediction is expected hard to correlate on a composite flange since it is not properly significant on coupon specimens.

3.2. Element level

Various experiments have been conducted to validate the design approach of the drive shaft. This corresponds to the test of reduced specimens of the drive shaft, according to the test pyramid defined on Figure 2. These shortened shafts help to increase the modelling knowledge about specific areas such as the connecting radius and the flange. These areas are not studied in the literature because this work provides insight about an innovative manufacturing process and composite stacking. With this gap in mind, efforts have been made to comprehend the mechanical behavior and the strength of the shortened shaft flange and put this knowledge into an engineering model. The purpose of this model is to provide a theoretical foundation to properly size a composite drive shaft based on specifications. Shortened shaft is a good reduced real part of a real shaft because stress in the flange is identical irrespective of their length (while the shaft is not “too short”), which is helpful to reduce computation time and to save a lot of material during prototyping and tests. This assumption has been validated with two shafts models with identical flange definitions but different lengths and the final displacements and stresses were the same.

Several experimental tests have been performed to provide data to develop these engineering models of the composite flange, focused on reduced length shafts. These tests are about the failure torque level to which the composite cracks and fails, giving a better insight about torque transmissibility of a composite flange design. This campaign includes the breaking in torsion of the following shortened shafts: one shaft (S1) with design D1 and material M1, followed by three shafts (S2, S3, S4) with design D2 and materials M1, M2 and M3, and finally two shafts (S5, S6) with design D3 and materials M3. Shaft S1 has informed about the material capability and the manufacturing process, which was not suitable for the application, leading to the research of an alternative material. S2, S3 and S4 shafts have been used to narrow the design of the flange throughout the composite stacking sequence and study the performance of a new material.

The first approach used to develop an engineering model of the fully composite drive shaft is the development of a midsurface 2D finite element model with Patran software. This approach is motivated by the willingness to have a “simple” model to provide reliable and fast data in preliminary design process. Properties used are the PCOMP elements with the definition of the stacking sequence of a preset orthotropic material, which is defined by the main properties obtained from the coupon tests campaign. The stacking sequence is defined to match the one obtained after the manufacturing process, taking into consideration the final properties of the composite shaft. The shaft is meshed with 1.0 mm CQUAD4 elements, as visible on the Figure 4, associated with PCOMP properties defined. Three fixation holes from one side have their displacements locked in every direction, and the torsional loading is applied through an RBE3 element (also visible on Figure 4 in purple).

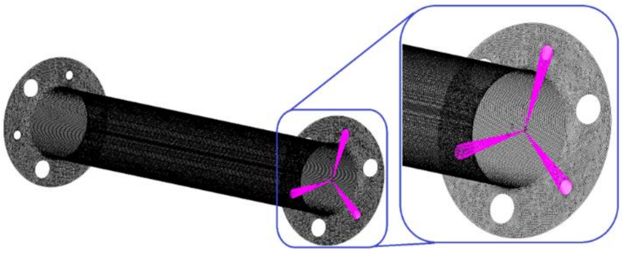

Figure 4: Mesh detail of the 2D midsurface composite shaft model

The first approach used with this reduced-length shaft model is the analysis of failure areas and the impact of geometry and stacking sequences on failure levels. TH criterion has been used for this task since it is the most common, and conservative, failure criterion for composite applications. The following parameters have been analyzed with the 2D PCOMP model to assess the impact on the failure criterion:

- Add of plies on the flange: increase the strength of the flange by increasing its thickness and improve the way fibers spread the stress in the shaft. The bottom-left Figure 5 shows a configuration with minimal stacking while the bottom-right Figure 5 demonstrates the reinforcement brought by additional plies on the flange surface.
- Add of plies in the connecting radius: increase the strength of this area by the same mechanism as for the flange though an increase of the radius. Potential of strength gains need to be considered with the manufacturing capabilities of the analyzed solution.
- Torque application on the hole (by obstacle, by friction or by a mix of both): highly impact the strength of the fixation holes depending on the way torque is applied to the shaft. If the torque is only transmitted by obstacle, peening will appear with a spike of stress as it is visible on the top-left Figure 5 In the case of a torque transmission by friction, this stress spike greatly decreases as illustrated on the top-right Figure 5 A combination of both will induce a stress level in between, depending on the slipping moment moving from a friction transmission to an obstacle one.

Holes diameter: is the last design parameter studied in this study because of an assembly design constraint. Various diameters have been analyzed and the stress value increases with the increase of the diameter since it approaches the connecting radius. This creates a combination of form and hole factors increasing greatly the stress in the area.

The sensitivity analysis provides information about the critical areas, identified as the fillet radius and the area in compression by the fixation. These regions are the most critical section of the shaft, to which can be added the fillet radius under the non-fixation holes depending on their diameter and closeness from the fillet radius.

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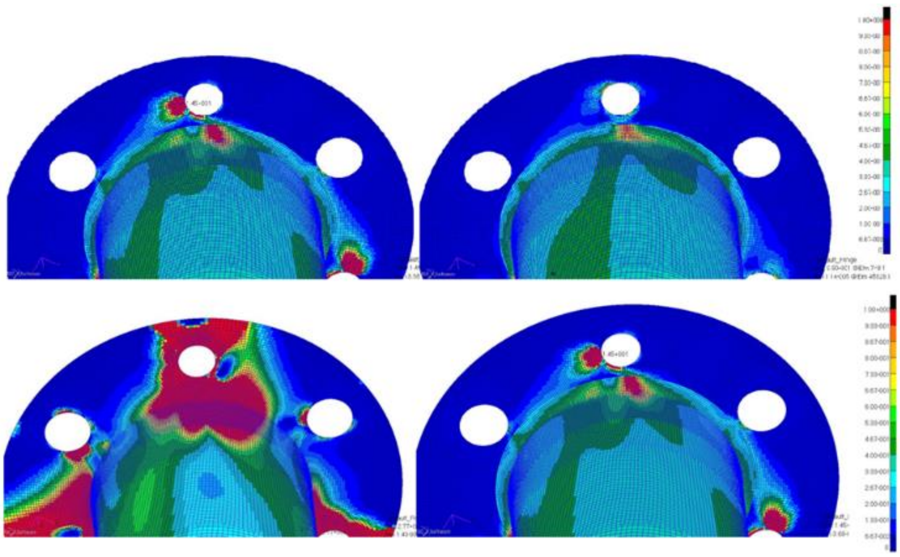

Figure 5: Sensitivity analysis with Patran setup on Tsai-Hill criterion

Based on this analysis, the failure criterion level is influenced by the number of layers and the angle of the plies: the more layer and the closer the angle to 45°, the greater the mechanical strength. However, even if +/-45° stacking is the most optimized sequence for torsional strength, is it rarely adapted to the frequency positioning of the shaft, and the full transmission drive line. Composite shaft sizing depends on both torsional strength and frequency positioning, so the stacking sequence has to be adapted to both specifications

Another limit of the approach is the consideration TH criterion as reference. It is known that this criterion is conservative, mainly because of the matrix tension. According to [Ref. 4, 9 & 10], a better modeling approach to size composite fixation holes is through the Yamada-Sun (YS) criterion, which is TH criterion neglecting the matrix loading, because the matrix allowable in tension is often limiting the failure level due to its intrinsic low strength. According to the literature, this approach is less conservative since the matrix can withstand some damages without propagating failure in the flange. Even with alternative failure criteria like YS, the failure level predicted by numerical model was widely below the failure level measured by experimental mean on shaft S2, S3 and S4, by 40 to 70% depending on the criterion used. This indicates the model is too conservative to predict accurately the failure level, preventing from designing an optimized composite shaft only with engineering tools. To improve the prediction accuracy of the engineering model of the composite flange, a new model is developed with Abaqus software.

Based on the lack of precision between a 2D midsurface PCOMP model and experimental results obtained, further investigations have been made with another modeling approach. Since the torque application is made through a mix of friction and obstacle transmission, this new model includes screw and contact modeling. Every component of the fixation is modeled such as screws and attachment plate. The shaft is also modeled with a refined mesh of a combination of C3D8R and SC8R elements. Most of the shaft is meshed with SC8R elements according to Figure 6 (left), and the area around one fixation hole is made with a denser mesh of elements C3D8R. This element can take into account out-of-plane strain leading to a better modeling of the stress propagation in the connecting radius. We know this area is sensible thanks to the sensitivity analysis previously made because of the combination of holes near a radius and the radius itself. The refined meshing around the fixation hole is detailed on the Figure 6 (bottom-right).

The model is completed with screw and a plate to have a better modeling approach of the boundary conditions. Both screws and plates are modeled with C3D8R elements with aluminum properties. Boundary conditions are more sophisticated with such model than previous PCOMP model: preload of the bolt has to be defined to model the pretension in the screw and the torque transmissibility by friction at the beginning of the load application. In this model, the pretension if the bolt is setup to 10 kN based on the tightening torque and the friction coefficient. The torque is applied on the attachment plate, as it is applied by a torsional test bench, while displacements of the three fixation holes of the opposite side are completely blocked in all directions.

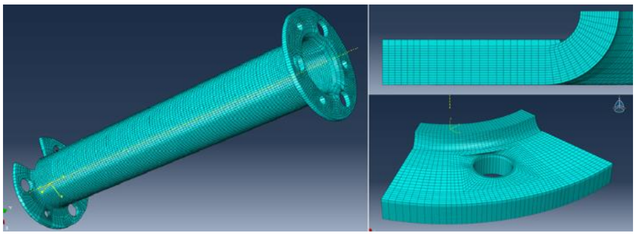

Figure 6: Composite shaft model on Abaqus setup

Failure criteria used with this Abaqus model are max stress and Hashin [Ref. 5], see Figure 7. This 3D failure criteria integrates out-of-plane shear to give a better insight of different stresses combination. Thanks to the 3D modeling of the flange, the stress distribution along the thickness can be analyzed around the fixation hole. It appears clearly that the torsional loading breaks open the hole under the shear stress, resulting in a fissure caused by tension on either side of the connecting radius under the fixation hole. This analysis results from the failure modes study avec the shafts S2, S3 and S4, visible on the Figure 7 below. This behavior is also depicted by this new model, showing a failure along the thickness of the flange at the level of the connecting radius.

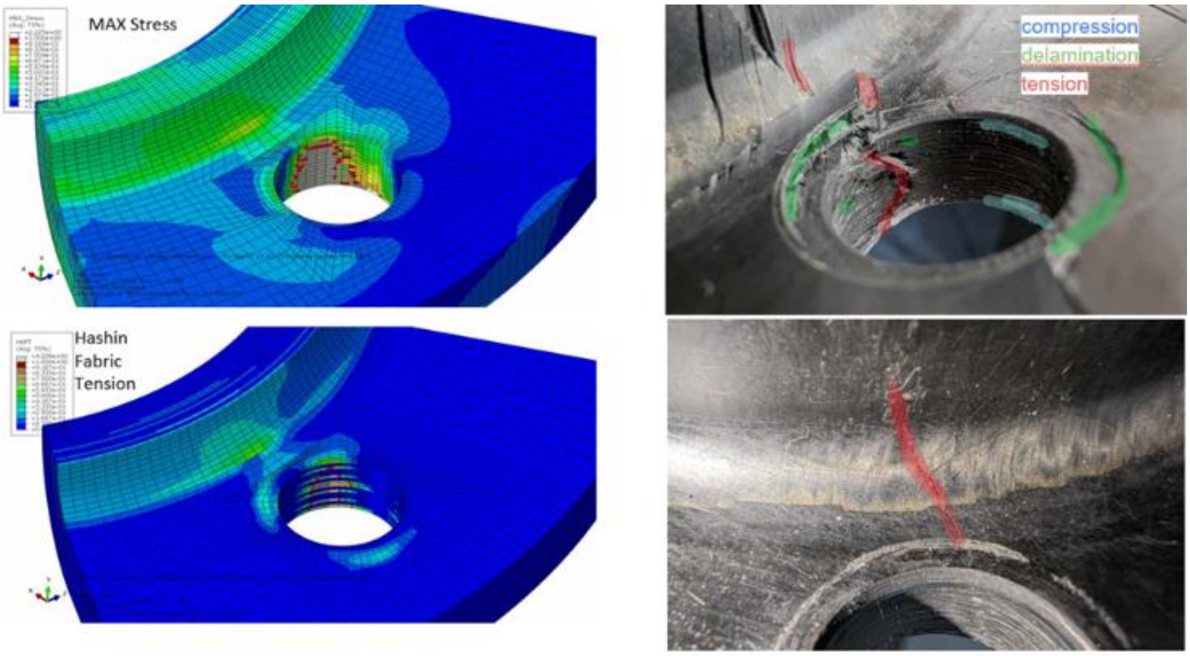

Figure 7: Comparison of failure mode between numerical model and experimental results

Cost of the model and multiple parameters. The model seems to accurately capture the fracture pattern in the flange thickness. The same fracture pattern happens in every fixation hole and most of the six connecting radii after the failure of shafts S2, S3 and S4. Thus, most of the mechanical behavior is captured by this model but the torque level of failure is not as precise as the stress distribution. Various configurations of bolt pretension and friction coefficient are studied on Figure 8. On the first subfigure (top-left), the first failure index to reach the failure level of 1.0 is the matric in tension, near 1650 N.m. This torque level would ensure a compliant design regarding the specifications, defined in the range of 1500-1750 N.m. Problem is that the actual failure torque is in the 2700-2900 N.m range, far away from the model prediction. This is explained by multiple factors. In the first place, the experimental setup present inherent uncertainty about the real boundary conditions, mounting gaps or measurement chain for example. Then, uncertainties occur in the modeling capability of the model, its potential to capture complex mechanical behavior of composite properties. Finally, the last source of uncertainty comes from parameter values used in the model. Many parameters are used in this model, including material properties and boundary conditions. Material data properties are derived from tests carried out on coupon specimens, while boundary conditions are a mix of measured and estimated data from the experimental setup. Tightening torque and friction coefficient are estimated and have an inherent uncertainty. A sensitivity analysis has been performed on these two parameters, visible on the Figure 8. Results demonstrate a massive impact of these parameters on the failure level of the Hashin criteria. The higher the screw pretension, the higher the failure torque, just as the higher the coefficient of friction, the lower the slope of the failure criterion - and hence the higher the failure torque. From these modeling, with a high range of values for the two parameters, the failure level of the experimental setup is not matched, even on the bottom-right Figure 8, where matrix compression reaches failure level around 2300 N.m. The engineering model developed is thus too conservative to predict accurately the failure level of a composite flange. Further investigations could be explored with damage law for composite mechanical law. It is motivated by the Hashin, TH or any failure criteria that is focused on the first ply failure, and not the capacity of a part to undergo a load even with some local failure. This explanation is preferred because many cracks have been heard during the progressive torque application before the final failure, during a wide range of torque that has not been recorded to compare with the developed engineering model. This is the main outlook to further improve the engineering model of the composite drive shaft developed.

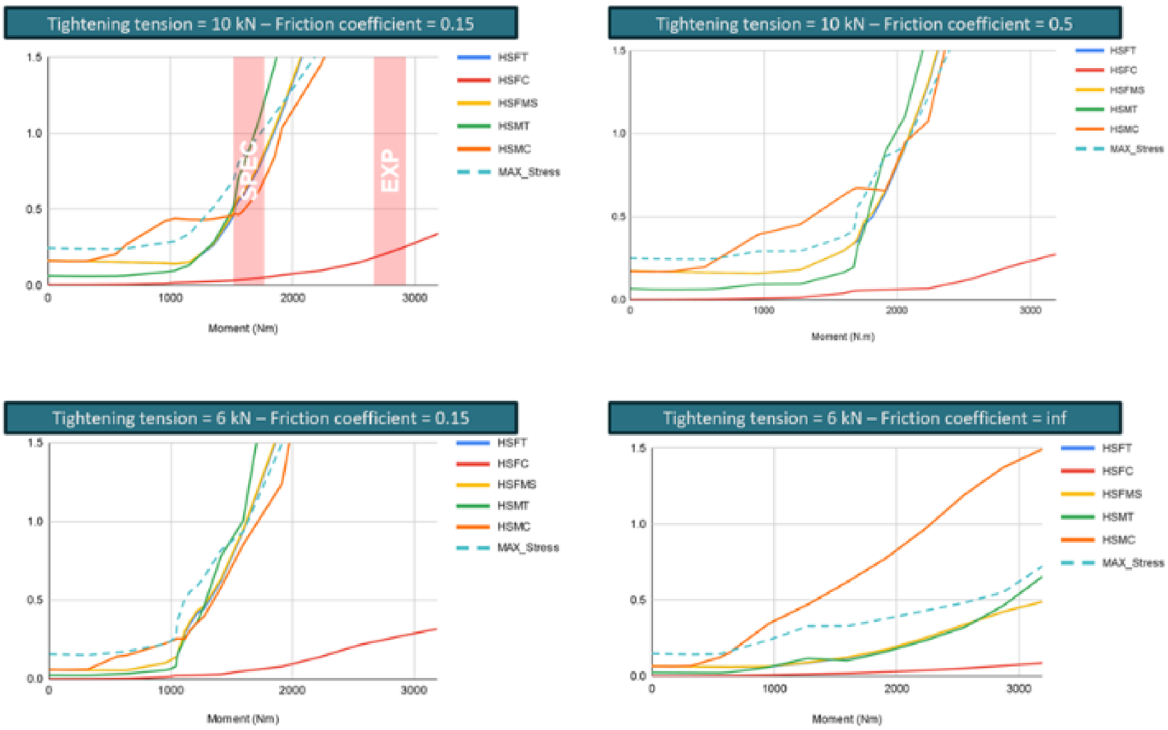

Figure 8: Sensitivity analysis of tightening force and friction coefficient on Hashin failure criteria

Since the engineering models are not capable to accurately capture the failure level of the fully composite drive shaft, torque transmissibility of the shaft is demonstrated by experimental mean. Two reduced-length shafts, S5 and S6, with the final flange definition have been manufactured and tested on torsional bench. S5 shaft mounted on the torsional bench is presented in Figure 9. In order to take into account the uncertainty of the material properties, the manufacturing process, the boundary conditions and even the installation and maintenance of the shaft in the aircraft, the shaft need to respect the specifications even with degraded conditions. It means that the composite could be damaged, so a controlled impact is made on the composite tube, to create a Barely VIsible Damage (BVID), with which the shaft needs to respect design constraints.

Shafts S5 and S6 shafts are reduced-length composite drive shaft with the final design of the RECOMPOSE shaft flange. They have been impacted with a predefined level of energy, then tested on the torsional bench up to failure. With these degraded material conditions, they exceeded the ultimate torque from the specifications by more than 20%, giving margins to optimize the product – so the final weight.

Figure 9: Torsional bench setup with shaft S5

4. MANUFACTURING OF THE COMPOSITE DRIVE SHAFT

4.1. Manufacturing process

The first manufacturing process used to develop a fully composite drive shaft has been filament winding. This process has been used to develop several tens of shafts, but has demonstrated limits regarding specifications of the shaft, in particular about winding angle limited in a constrained range, due to the specification of the winding process developed for this special application and patented. These limitations led to the use of rolling process instead of the filament winding. Manufacturing operation of rolling is integrated in a global manufacturing process of composite drive shaft composed of three main subprocesses before delivery, detailed in Figure 10.

The first sub-process contains tasks to be carried out in a gray room, i.e. in a controlled environment. Among these tasks, two flows are identified: the consumables flow and the material flow. The first involves cutting and preparing the consumables required for the rolling and molding stages, while the second prepares the composite material for the rolling stage. Once composite material and consumables are used in the rolling process, the preform is obtained to continue the following sub-process: the curing cycle.

The second sub-process includes the steps for preparing the mold with consumables and preform. All these components are then assembled to prepare for the composite polymerization phase. This curing stage is specific to each composite and consists of several temperature rises and curing stages. This step is very important for the final quality of the shaft in terms of material health. Once the polymerization cycle is complete, the mold and shaft are cooled down - at a speed that depends on the material and the curing cycle. Finally, the composite shaft is removed from the mold, which is cleaned and treated for a new cycle. The result of this sub-process is a composite shaft that has not been machined or equipped.

Finally, the third sub-process covers the shaft inspection and finishing stages. The first task is non-destructive testing of the shaft, based on ultrasonic inspection to verify the composite material health. The aim is to identify the presence of inclusions, porosities or delamination that would otherwise reject the product. If the shaft health is as expected, it is then machined to remove excess material and to drill where necessary. A further inspection phase is carried out to determine the precise dimensions of the product using coordinate measuring machines inspection and, if necessary, a new ultrasonic testing inspection to check the material health around the machined areas. The shaft is then fitted with the necessary components and balanced to ensure its dynamic behavior. If all these steps have been validated, the composite shaft can be delivered to the final customer.

According to the process presented on Figure 10, the Figure 11 present the evolution of the state of the composite drive shaft. In the first place, there are only composite strip cutting (Figure 11-a) that will be assembly during the rolling process Figure 11-b. This assembly, called preform, is then put in the mold and assembled with various equipment to provide the raw composite drive shaft visible on Figure 11-c. The final shaft is then obtained after a control and machining removing the excess of material and drill holes, as represented on Figure 11-d

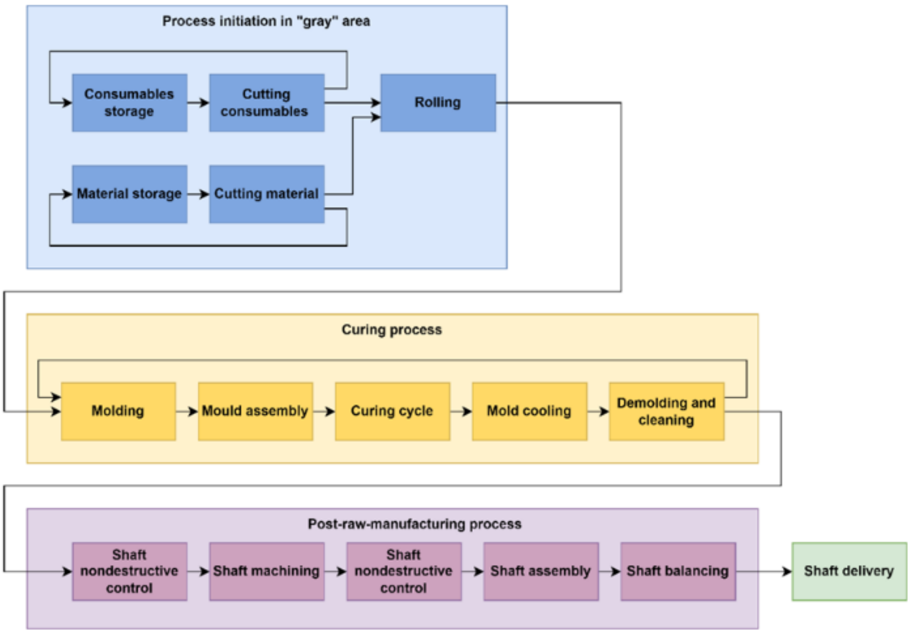

Figure 10: Manufacturing process overview

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Figure 11: Four steps of material evolution from a ply to a final composite shaft

The ultrasonic inspection phase is favored for controlling the material health of the composite shaft at controlled cost. Inspection can be carried out in two ways: manual or automated. In the first case, the tube is broken divided into zones as shown in Figure 12, on which a sabot is positioned to control the shaft, which will rotate to proceed to the data acquisition. Connecting radius and flange are then manually controlled by flexible and monoelement probe. The second way to acquire ultrasonic data is by using an automated mean of control like a pool inside which the composite shaft is immersed, and a probe is displaced along the shaft while it is rotating. This automated mean of control is currently under development within RECOMPOSE project in order to improve the development performance of composite shaft production.

Ultrasonic control returns various information with the use of four screens, as visible on the Figure 13. The first screen (top-left) shows the single signal at Y-axis observed at the probe axis. It is called A-scan and is used to observed in the thickness of the part. The second screen (top-right), called B-scan, shows the section under the probe at X-axis, giving a cross-sectional view of the part along the probe. The third (bottom-left) is called C-scan and provides an X-Y view of the part and represent the top view of signal passing through red gate (visible on A-scan). Finally, the fourth (bottom-right) is the top view of signal passing through green door (also visible on A-scan). The Figure 13 highlights the presence of a default in the tube. A default is identified when peaks appear on under the red gate on screen 1, when a “dense” area is identified on screen 2 and when a colored area is revealed on screen 3.

This type of default could be a delamination or an inclusion.

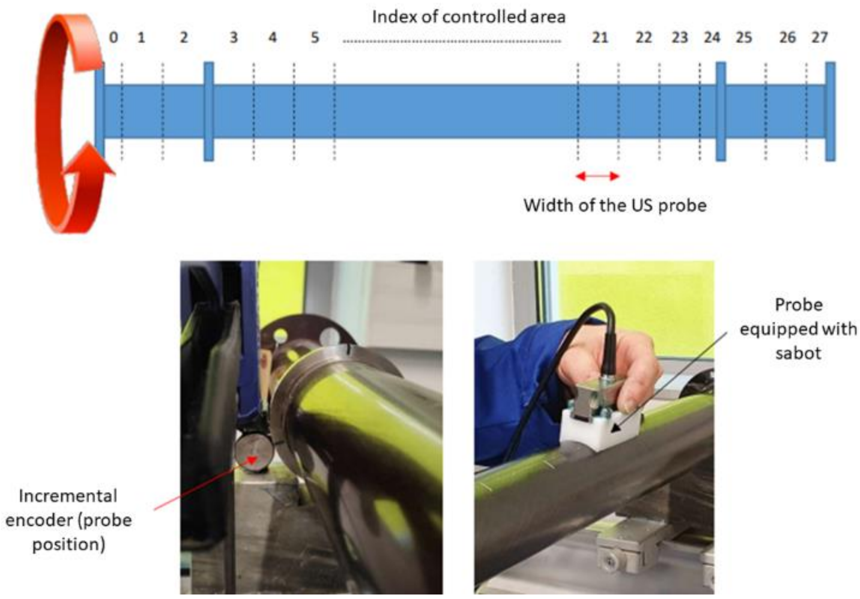

Figure 12: Nondestructive ultrasonic control setup

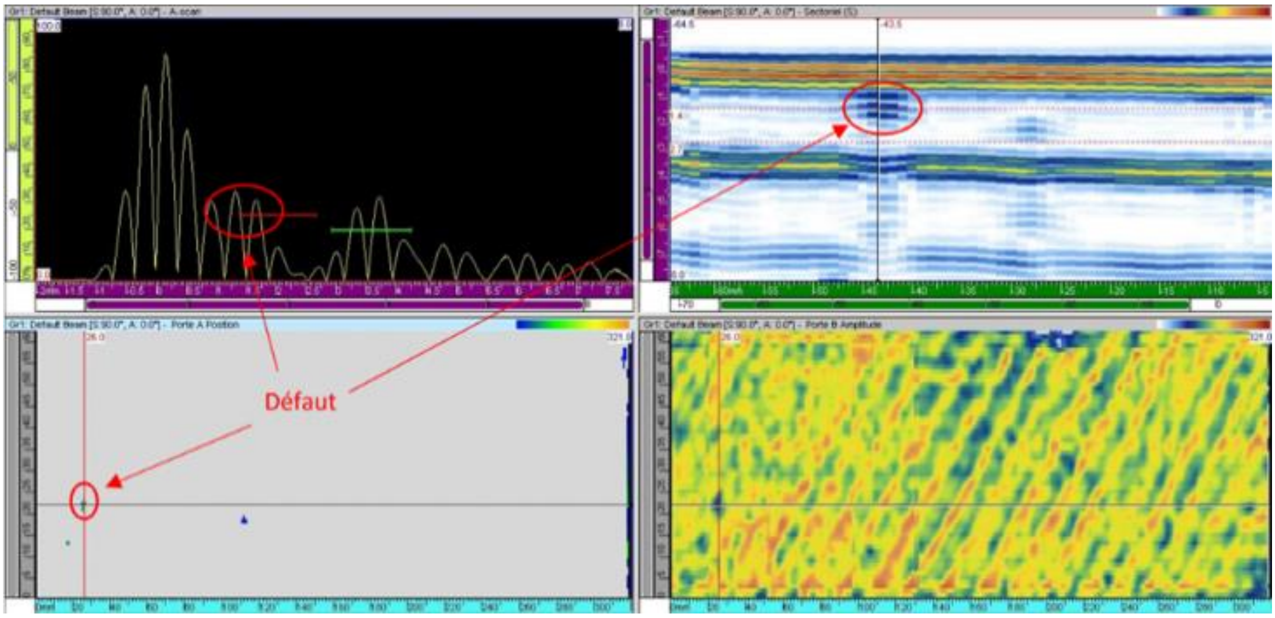

Figure 13: Example of ultrasonic control screens with an identified damage

All RECOMPOSE composite shafts have been inspected by this ultrasonic mean, and the material health has been diagnosed very good without defaults above 25 mm^2 in the tube. Surface defect ratio in the tubular section is lower than 0.1%, reflecting a very good material integrity. Defaults on the flanges, the most difficult parts of the shafts to manufacture, have been identified on the outer diameter of the flange. Most of these defects are small (<25mm^2) and on the outside of the flange, which should not affect the mechanical strength of the shaft.

4.2. Ongoing validation campaign

The design validation test campaign, currently in progress, aims to validate the design of the RECOMPOSE composite shaft, a full-length shaft, regarding the specifications. These tests will also provide a lot of data to pursue the development of engineering models, including stress value for finite elements models but also fatigue and dynamic data. A total of 3 composites plates and 12 composite shafts are to be tested, around four objectives, each one detailed in the following subparagraphs.

The first batch concerns the evaluation of environmental conditions on the mechanical properties of the composite. Coupon specimens are to be tested under shear loading within three different environmental conditions: the first one is the reference state with ambient temperature and relative humidity (RH), the second one is tested in hot environment (>100°C) but ambient RH, and last one is tested in ambient temperature after aging in humid environments. Specimens are tested in shear since it is the most representative loading of the composite shaft. Experimental results will inform about the loss of property in operational environments, conducting to the identification of margin of the shaft design regarding the specifications.

The second main batch of test is composed of RECOMPOSE composite shaft tested in torsion up to failure. It is divided in a test of a healthy shaft, to get the nominal failure torque, and of an impacted shaft with BVID. The second one gives insight about loss of mechanical properties induces by a quantified damage of the shaft. The composite drive shaft should respect the specifications even with this damage to be declared compliant. This approach in composite product validation is used to prevent most uncertainties from the manufacturing variability, the maintenance phases or the operational phases.

The third batch, and the longest, is related to fatigue tests of the shafts. Fatigue tests are used to evaluate the mechanical strength over a long period of alternated loading, in torsion in this case. The favored approach is the construction of the fatigue curve S-N of the composite drive shaft. This curve defines the expected number of cycles the shaft can complete before breaking for an equivalent stress in input. This stress is put into perspective with the fatigue loading in operational conditions measured on the aircraft. The purpose of the tests is to define the shaft fatigue curve by identifying the stresses for different numbers of cycles, around 10^4, 10^5 and 10^6. The two first values should be in the “curved” section of the S-N curve, while the last one should be the value to which the lifetime is considered infinite. One more shaft is also to be tested in fatigue with a damage, giving insights about the potential knock down coefficient to apply on the fatigue curve.

Finally, the last batch of test concerns the dynamic behavior of the composite shafts, assessed on a representative subassembly of the transmission drive line composed of two shafts and three supports, all developed during RECOMPOSE project. These tests, in the first place without BVID, and then with, aim to inform about dynamic stability and level of vibrations considering radial misalignments of the supports. Misalignement is considered regarding operational condition levels to be simulated on the dynamic test bench. Dynamic test will also be considered with impacted shaft to ensure the stability and the integrity of the shaft at high rotational speed in deteriorated conditions.

Experimental validation will generate a lot of data to analyze in order to better comprehend mechanical properties of the composite drive shaft, and specifically about the composite flange. This will help to improve engineering model already developed about the prediction of failure level.

5. CONCLUSIONS AND OUTLOOK

This study demonstrates the feasibility of manufacturing a fully composite drive shaft in accordance with specifications since reduced-length shafts failures all exceed ultimate torque expected. The shaft handled more torque than expected giving margins to optimize the properties and geometry of the shaft in near future.

However, efforts still need to be made to develop engineering models able to predict failure level of a theoretical composite shaft design. Discrepancies between expected and observed failure torque with both numerical models developed should be reduced by the development of a new model. This new model could be based either by a different material properties modeling (with damage approach) or by extrapolation of experimental results if enough data is collected. In particular, the study of failure mode on coupon tests, considering the damage of the material, is an interesting pathway for further investigation.

From manufacturing point of view, the process demonstrates maturity and the quality the fully composite drive shaft produced. The process has been optimized during the RECOMPOSE project with the identification of workstations to automate to improve the manufacturing performance.

The experimental validation campaign in progress will bring various data to improve both engineering models and design process. These processes, data, models and all things developed during RECOMPOSE project will be continued in future composite shaft development project targeting flight certification before 2030.

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