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H160 HELICOPTER: DEVELOPMENT OF A CARBON THERMOPLASTIC HUB

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ABSTRACT

Airbus Helicopters is developing for the new helicopter H160, a main rotor hub made of carbon fiber with the thermoplastic resin PEEK, a key innovation for such rotor systems. This paper presents the Airbus Helicopters experience of rotor composite components based on thermoset resin and their specificities particularly the thickness and the fatigue loading. The key advantages of carbon thermoplastic material are then underlined. The mastering of the manufacturing process is a challenge and this paper presents the process applied in order to obtain the right quality level. The sizing and the certification process are also described. The development plan put in place will lead to be fully compliant with the last requirements coming from regulations CS29. Some key results are discussed.

Notation

- AH: Airbus Helicopters
- A6m: mean fatigue limit for 10^6 cycles
- CAI: Compression After Impact
- DHC0: Dynamic Helicopter 0 (test bench where the full H/C is tested)
- ETW: Elevated Temperature Wet
-G_I and G_{II}: Energy release in mode I and mode II
- ILSS: Inter-Laminar Shear Stress
- Tg: Glass transition temperature
- TMA: Thermal-Mechanical Analysis
- TP: Thermoplastic resin
- TS: Thermoset resin
- REACh: Registration Evaluation Authorization and restriction of Chemical substances
- RHC: Rotor Head Center
- RTD: Room Temperature Dry
- UD: Unidirectional
- σ_R: failure stress

1. Airbus Helicopters experience on composite rotor components

Airbus Helicopters has a great experience of composite components on rotors. It could be mentioned the tail and main rotor blades, which equip all the AH helicopters since the end of sixties. The technology is mainly based on spar made by UD glass roving and the skin composed by carbon and glass fabrics. Concerning rotors there are Starflex® hubs which equip the Dauphin and Ecureuil families (around 1800 H/C; Fig 1 and Fig 2). This design is based on a flexible arm and a thick part which carry all the loads. It is made by glass fabrics. The plies of the arms are oriented to +/- 18°. The central part has a quasi-isotropic lay-up. The number of flight hours reached today is around 34 million flight hours.

Fig 1: Ecureuil main rotor head

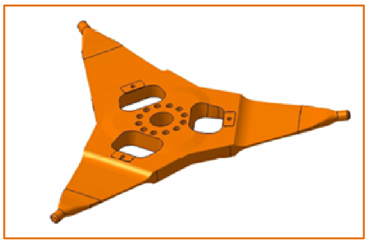

Fig 2: Ecureuil Starflex hub

Starflex® technology has been able to perform evolution during 40 years [1].
This duration is remarkable and has been possible due to the continuous improvements done all along the years.
These improvements were necessary due to many factors such:

- Material evolution,
- New versions of Helicopters with increased flight domain,
- In service experience.

Another success is the H135 bearingless main rotor hub composed in particular by the flexbeam (see Fig 3 and Fig 4). This part made by UD glass fiber is flexible in torsion, in flapwise and lead-lag direction and by this, eliminates the pitch, flap and lead lag bearings.

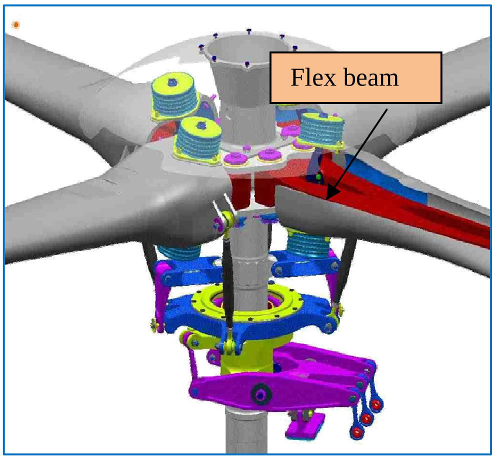

Fig 3: H135 flexbeam

Fig 4: H135 main rotor head

Note that all these rotor parts are in glass fiber associated with thermoset resin.

A specific technology has been developed for the TIGER based this time on carbon fiber. The rotor hub is composed by two thick plates with fiber orientation alternating between +/- 45° and 0°/90° (see Fig 5 and Fig 6).
The behavior of this part is remarkable knowing that this military H/C is operating in severe conditions.

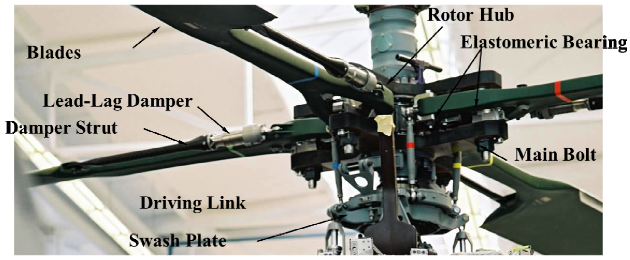

Fig 5: Tiger main rotor head

Fig 6: Tiger carbon plate of the hub

The main specificities of such rotors parts are:

- High thickness of the part,
- Highly fatigue loaded in high cycle fatigue and low cycle fatigue modes,
- They are critical part,
- Some parts are designed with stiffness constraints,
- The loads are transferred to the main rotor shaft through a bolted connection.

Following all these success stories, AH is developing for the new helicopter H160, a main rotor hub made of carbon fiber with thermoplastic resin PEEK. It is based on a Spheriflex technology composed of five blades (Fig 7).

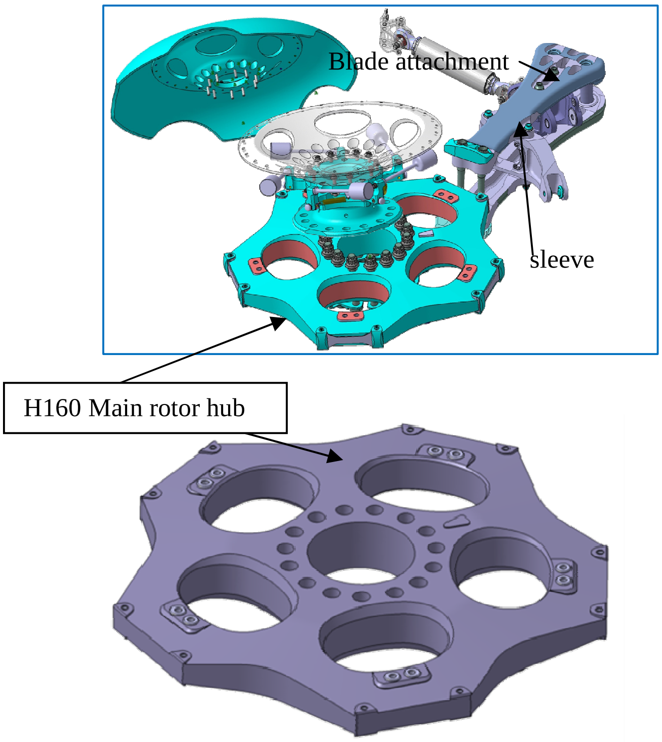

Fig 7: H160 main rotor hub

2. Interest of Thermoplastic

Thermoplastic resin PEEK has been chosen regarding mechanical characteristics improvement in comparison with some TS resin (class 180°C). There are two important points to note (Fig 8 and Fig 9):

- A better strength behavior of the TP compared to the TS in fatigue and static mode. In the most severe conditions after ageing (ETW), TP is 1.28 x higher than TS in static mode and 2.13 x higher in fatigue,
- A lower effect of the ageing in particular in fatigue.

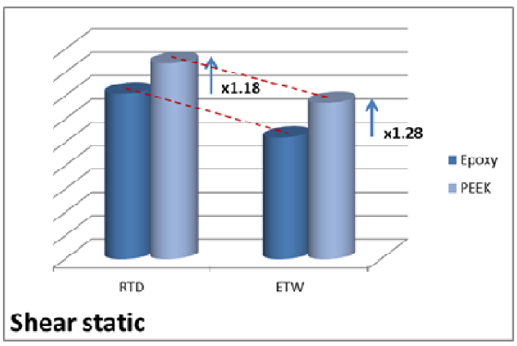

Fig 8: TS and TP shear static values

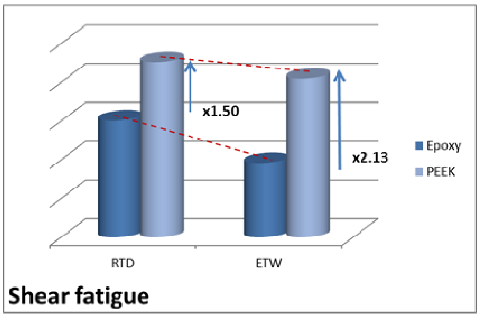

Fig 9: TS and TP shear fatigue values

Literature underlines also a significant higher stress intensity factor K_{1C} value comparing to thermoset resin [3].

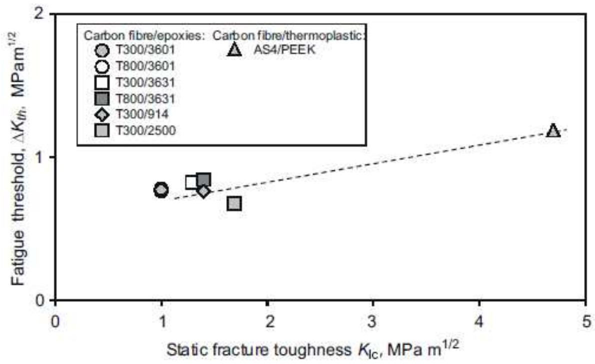

Fig 10: K1c versus TP and TS (Fig 11.9 from [3]).

TP shelf-life before consolidation and storage conditions are less stringent than TS.
Good resistance to environmental influence (de-icing agents, cleaning agent, ultraviolet light) has been also demonstrated through coupons.
Thermoplastic resin is “environment friendly” with no chemical reaction during transformation and no solvents inside (regarding REACh regulation).

The previous thick parts described in paragraph 1 are based on thermoset epoxy resins (glass fiber or carbon fiber) and press polymerization piloted by exothermic reaction. The H160 rotor hub is based on a new type of resin and manufacturing approach with a consolidation cycle by compression. The material chosen is the thermoplastic prepreg fabric PEEK/Carbon T300J.
The manufacturing process is using an un-tacky material, with a mold composed with different tooling parts which are individually piloted in temperature.
The thermoplastic consolidation process requires temperatures significantly higher than for conventional thermoset materials (approximatively 400°C).
The main difficulties are the temperature homogenization all along the process, and the

control of the thermal differential expansion between the material and the mold.
The mechanical and thermal properties of the resin TP and the carbon fibers present quite different characteristics and also strong anisotropy. For example the carbon fiber has a coefficient of thermal expansion near to zero and the PEEK resin has a nonlinear behavior versus temperature.
The crystallinity ratio depends on the cooling rate (Fig 11 from [5]), knowing that the crystallinity level could impact significantly the mechanical properties.

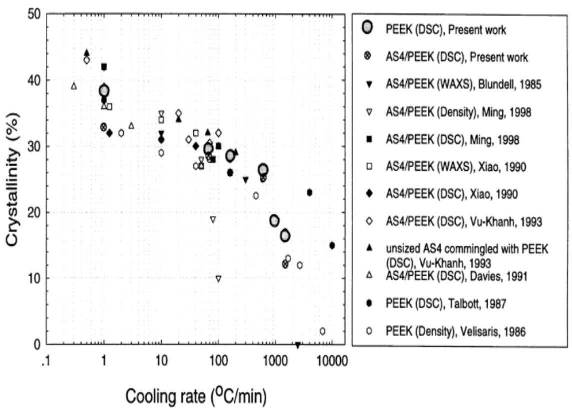

Fig 11: Crystallinity rate versus cooling rate

The last part of TMA curve (Fig 12) shows a strong evolution reflecting not a thermal expansion but a change of phase (solid - liquid) associated to a resin volume increase.
On this graph the expansion coefficient appears to be roughly linear between the Tg (140°C) and 300°C. Other information available on this material shows a "peak" of expansion at 340°C, corresponding to the PEEK fusion.

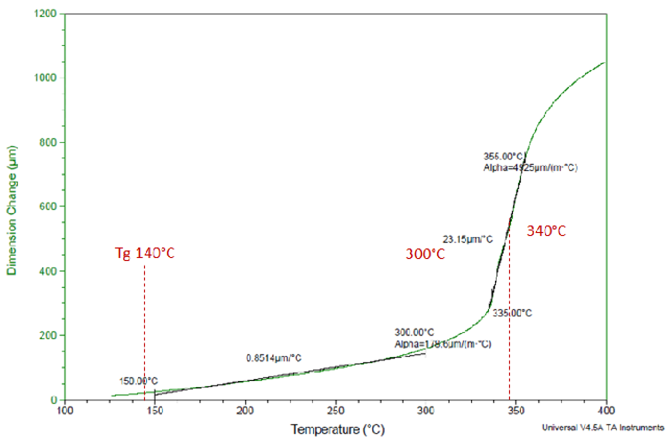

Fig 12: TMA curve

So it is important to master the temperature and the pressure cycles in order to optimize the process and consequently the mechanical properties (Fig 13). This flexibility on parameters adjustment permits to adapt the consolidation cycle to thick and complex parts, in comparison with TS cycle piloted by exothermic.

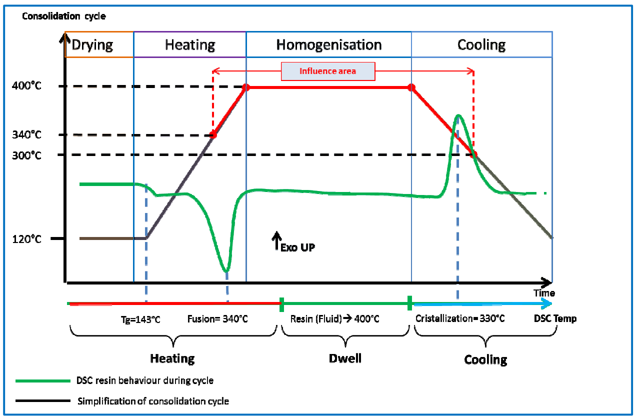

Fig 13: Overview of the consolidation process

3. The Manufacturing process: A challenge

A first composite rotor hub with thermoplastic matrix and carbon fiber has been made in the framework of a demonstrator. It has been tested successfully on a test bench and in flight. During the development phase, one main difficulty was to obtain the right quality level. This first experience has shown that the manufacturing key issues are:
-The consolidation cycle strategy due to the thickness of the part,
-The suppression of porosities, waves, micro delamination in the thickness variation areas,
-The high temperature process inducing geometrical constraints and dilatation effects.

In order to master these key characteristics and to confirm previous trials, the maturity has been improved through tests on technological parts. These operations were done on the basis of an evolutionary mold, leading at the end to the creation of a geometry part close to “2/5” of the hub.
The part dimensions were chosen to be representative of the hub, while respecting the size capacity of the laboratory press infrastructure.
The principle was to increase the geometry complexity step by step.

Step 1 (Fig 14): The goal was to validate the feasibility of a constant 85 mm thickness TP carbon part.

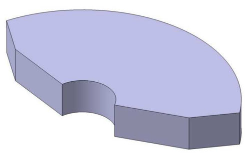
Fig 14: Constant thickness part

It has been obtained and demonstrated:
- An excellent quality level (% of porosity, crystallinity rate, waviness…),
- The controllability of such Carbon/PEEK part.

Step 2 (Fig 15): The goal was to validate the feasibility of a part with variable thickness (85 mm to 32 mm).

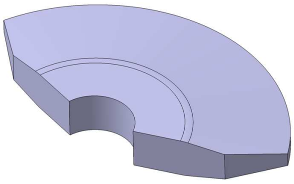

Fig 15: Variable thickness part

The thermal cycle has been adapted for the evolutionary thickness area. But due to the sliding of some plies in this area, some porosities and waviness were created. The final optimization has only been reached during the step 3.

Step 3 "2/5"(Fig 16): The goal was to validate the feasibility of a part with variable thickness and centering pieces which are parts of the mold.

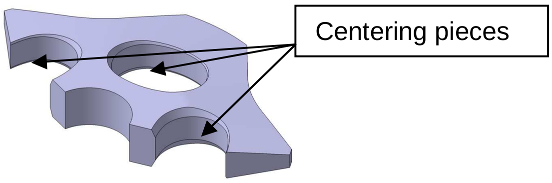

Fig 16: Variable thickness part and centering pieces

This third step has frozen the major process parameters such as:
- The centering pieces positioning,
- Tolerances/gaps required by the centering piece,
- The stacking sequence particularly in the variable thickness area.

The process reproducibility was also established through these manufactured parts "2/5". The downstream industrial phases including machining, drilling and finishing operations have also been developed at this time. Finally the manufacturing process has been validated for thick parts under compression process using a complex metallic mold.

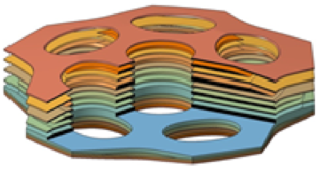

Fig 17: Stacking sequence

Step 4: Manufacturing of the complete hub (Fig 18). Only some adjustments were necessary thanks to the previous steps, and it has been achieved in a short time.

Fig 18: H160 main rotor hub

4. Sizing phase

The hub is loaded in flight by:
- Centrifugal load,
- Main rotor torque,
- Lift load,
- Rotating bending moment,
- Rotating shear load.

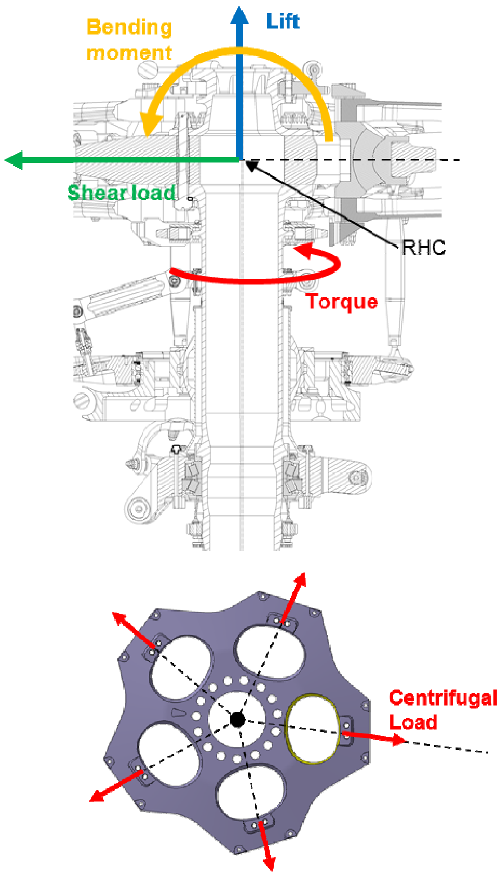

Fig 19: Main rotor hub loads

These loads generate different stresses in the carbon fabrics of the hub:

- Tensile (warp / weft),
- Compressive (warp / weft),
- Bending (warp / weft),
- In-plane shear stress,
- Inter-laminar shear stress (ILSS).

In a first step, static and fatigue tests on standard coupons have been done under tension, compression, bending, in plane shear, ILSS, impacts,…Different environmental conditions were studied. The goal was to have the complete material data base (n plies of fabrics 0°/90°).

In a second step, complementary tests have been performed on technological thick specimens (about 20 mm thickness) with the same stacking sequence as standard specimens but also with quasi isotropic lay-up. These specimens are coming from parts which geometry is close to the hub or cut out from hub during the development phase (paragraph 3).
From these studies design values related to the hub have been issued.

For such thick part the compression mode is not critical, and two main failure modes have been investigated:

- Static mode: there are two kinds of failure, the resin and the fiber. The fiber is the critical failure mode, and the most representative coupon is the bending one (long bending tests, see Fig 21). The resin behavior is established through short bending test (Fig 20),

- Fatigue mode: As the fiber is not significantly sensitive to fatigue (in tensile mode), it is the resin which is studied. The most representative coupon is the bending one (short bending tests Fig 20).

For the hub case, the resin failure does not lead to a complete failure but local degradations.

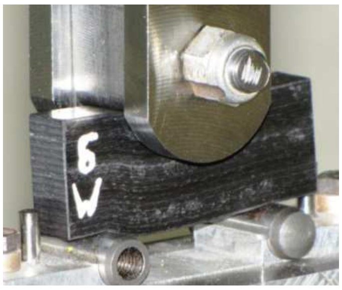

Fig 20: Technological specimens “3 short bending points ” test

Fig 21: Technological specimens “3 long bending points” test

After the manufacturing process optimization, the static failure values from standard coupons (0°/90°) are quite in accordance with the technological ones (thicker ones and quasi isotropic lay-up). For this comparison standard computation tools have been used. The ILSS values in static and fatigue are quite close between standards coupons and technological ones.

Concerning the ILSS fatigue behavior, two different areas have been underlined (Fig 22):

- From 1 cycle up to around 30 000 cycles there is a significant effect of the fatigue, characterized by an important slope,

- From 30 000 cycles up to 10^7 cycles the slope is low and similar to thermoset application. Extrapolation is done up to 10^9 cycles.

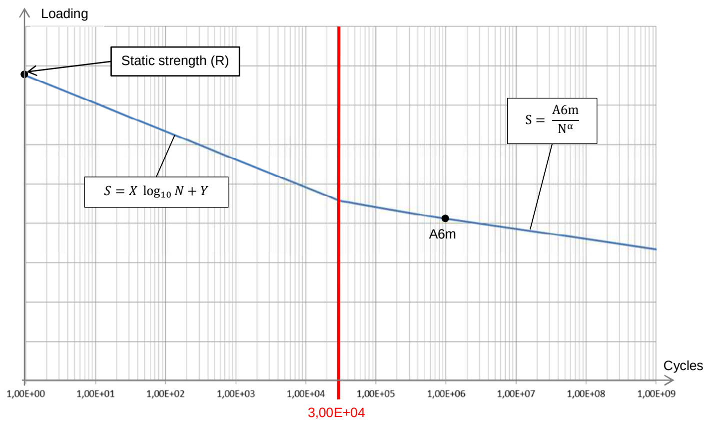

Fig 22: ILSS fatigue curve

The sizing has been done by FEM analysis considering an equivalent material (orthotropic) based on technological coupons and analysis. Critical areas regarding ILSS and fiber failures have been determined.

The FEM analysis has been validated by test characterization based on extensive strain gages equipment under single loads and different loads combination.
For the most loaded area the difference in terms of strain between the test and the computation is 3%.
In the other areas the maximum difference is 13%.

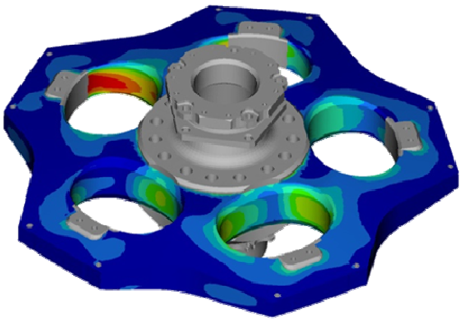

Fig 23: View of FEM results

5. Certification process

The certification process is based on:

- Stress analysis by FEM, in order to define critical areas,
- Static substantiation (CS 29: §303 305 307 613), in order to validate limit and ultimate strength,
- Damage tolerance and fatigue evaluation (CS29 §573), in order to define the hub service life limit and inspection intervals.

A building block test approach is retained (Fig 24) and the implementation is going on. The goal is to have an extensive knowledge of the behaviour of such parts and to master all the key issues.

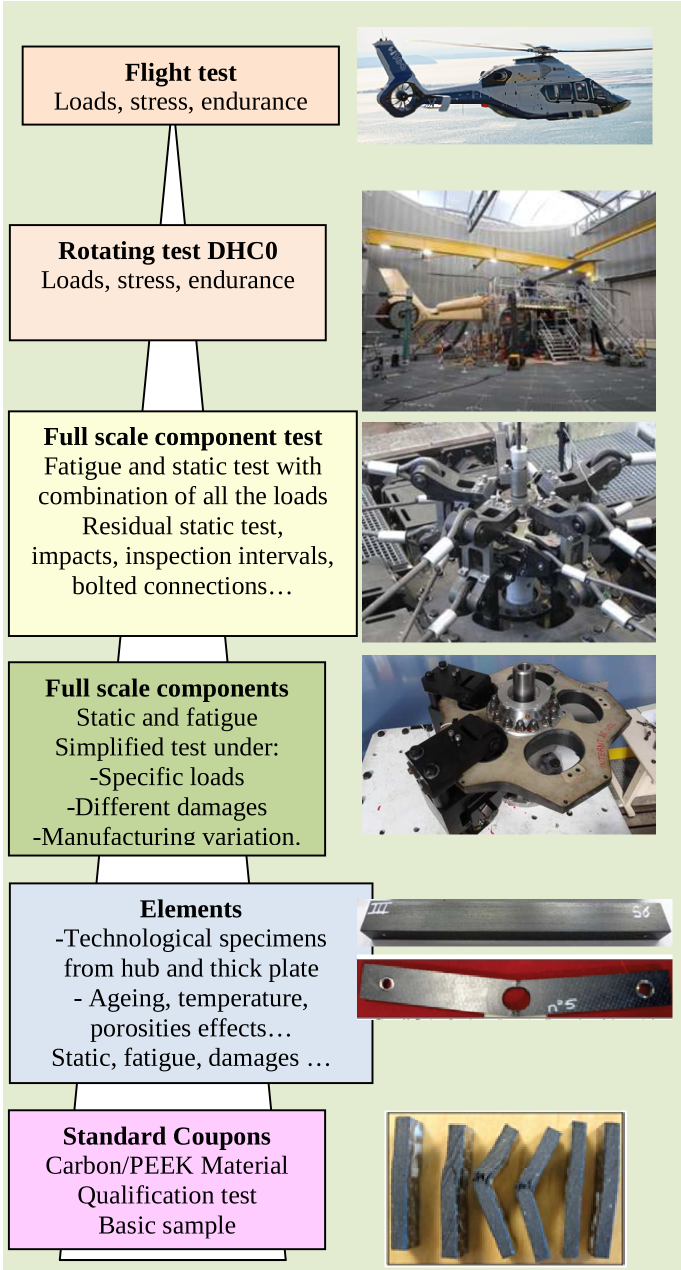

Fig 24: Building block test approach

6. Some results available today

Damage tolerance impacts: The PEEK carbon results are compared to 4 different thermoset carbon composite (UD and fabrics) after impact. For this purpose, CAI tests have been performed on standard coupons previously impacted up to 25 Joules. AH has demonstrated that 25 joules is the maximum realistic energy for mechanical components [2].
The Fig 25 shows the typical profile of a 4 mm thick impacted sample: as for thermoset material, delaminations and fiber failures are at the rear face.

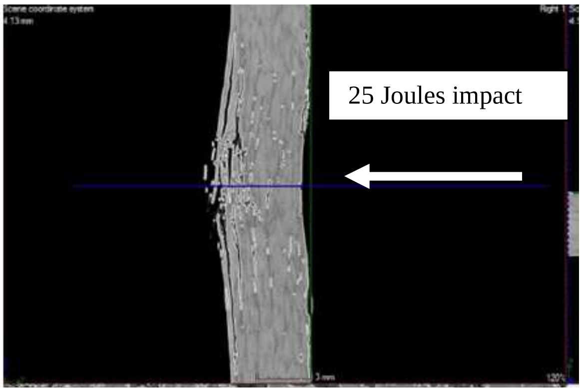

Fig 25: Carbon PEEK after 25 joules impact

Nevertheless a significant difference is highlighted: the static failure under compression (CAI) after 25 Joules is higher for PEEK carbon than the 4 thermoset cases (Fig 26).

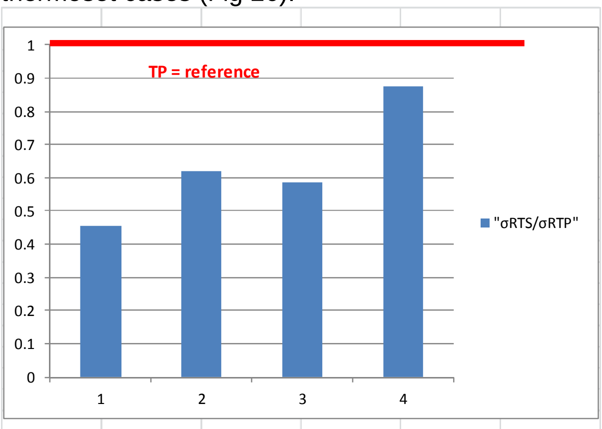

Fig 26: impact behavior - comparison carbon thermoset and carbon PEEK (σ_RTS/ σ_RTP).

This result underlines a good behavior of such resin type. This fact could be linked to what literature is mentioning: the high value of K_{1c} for carbon PEEK in comparison with carbon thermoset resin (Fig 10). The interest of thermoplastic resin for dynamic system components is confirmed.

Concerning the impact effect performed up to 30 Joules on the real hub, there are no significant damages as observed on the Starflex® hub [1].

Loading Frequency: effect on the material strength

Some authors have detected that the frequency has an effect on the strength by generating internal heating [3]. This effect could be simulated and checked particularly with ILSS specimens. This effect has been studied through technological specimens equipped with thermal sensors, under dynamic inter-laminar shear strength. The dynamic applied load corresponds to the fatigue limit at 10^6 cycles. Two frequencies have been tested: 5.7 Hz (1 per rev of H160 rotor) and 11.4 Hz. The thermal stabilization occurred after around 10 minutes. The temperature has been extrapolated at the specimen center and an increase of a few degrees Celsius was estimated, so with no consequence on the strength component.

Porosity effect:

Knock down factors have been established through fatigue and static tests on coupons issued from different technological parts (paragraph 3). These factors are quite low regarding the porosity level (Fig 27).

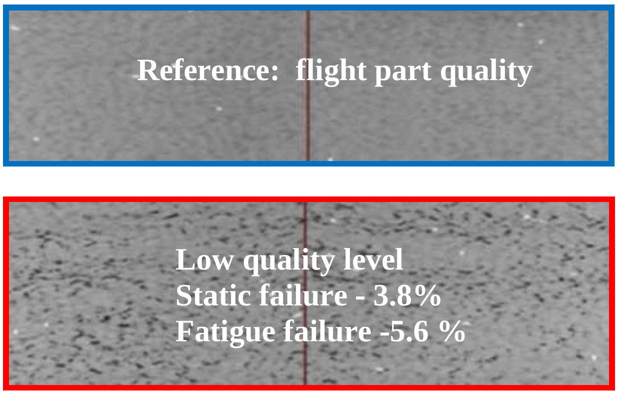

Fig 27: Porosity effect

Delamination propagation

In other to tackle any possible delamination in such thick parts, dedicated studies have been done on coupons and full scale components. A propagation curve (Fig 28) has been deduced from "four bending points" test [4]. The energy release rate (G) obtained is a combination between mode I and mode II propagation (G_I and G_{II}).

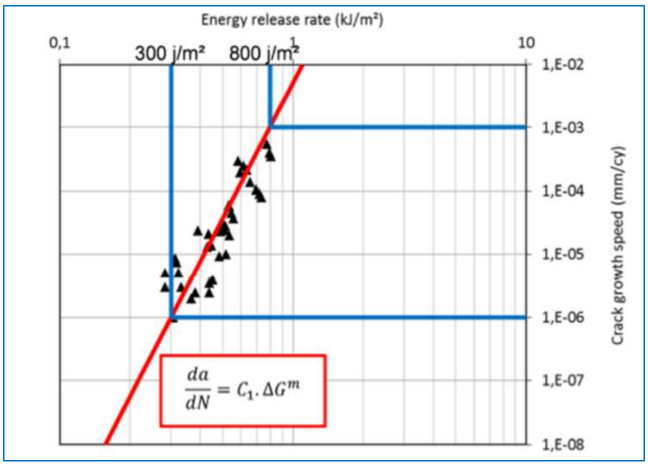

Fig 28: Carbon PEEK delamination propagation curve

Delamination propagation rate has been evaluated through full scale component. The propagation rate observed is quite low. Furthermore there is a threshold under which there is no propagation. These tests demonstrate a “fail safe behavior”.

Creeping effect**:**
This phenomenon has been assessed for the bolted connection between the composite hub and the metallic main rotor shaft. Dedicated studies based on coupons exposed to accelerated ageing and extreme conditions are still running. The first results show that this effect is not significant. In addition, tightening torque measurements are going on and will continue during 2 years on a full scale component exposed to natural environment effect.

7. Conclusion

The development of such a part presents huge efforts in different domains. In particular some key issues are now mastered as the sizing in terms of inter-laminar shear stress, the fatigue behavior and the production process.

This technology will bring benefits to the H160 helicopter:

- Weight saving participating to the H/C performance,
- A good fatigue and damage tolerance behavior, leading to a better customer satisfaction and a safety increase,
- A “green” aspect, with a material that is REACh compliant, the storage conditions being less stringent than thermoset material, inducing less environmental effects
- Lower manufacturing cost in comparison with metallic hub.

Fig 29: H160 prototype in flight

8. References

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