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THE STARFLEX® FLYING ALL OVER THE WORLD AND ALWAYS IN EVOLUTION

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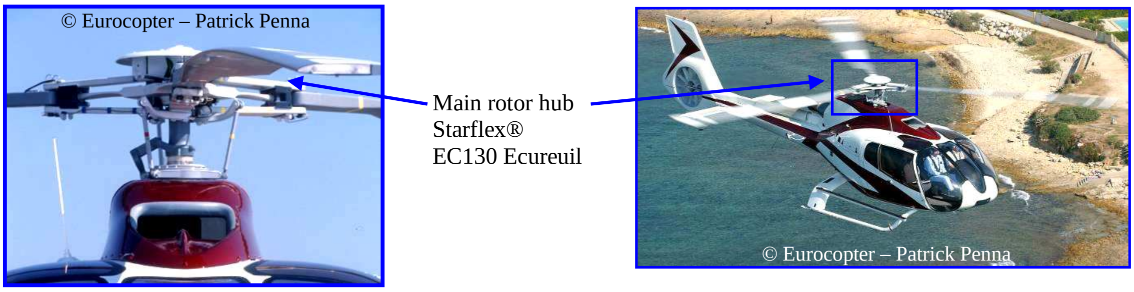
ABSTRACT



This paper gives an overview of the Eurocopter composite hub called Starflex®. The material is E glass fibre associated to an epoxy resin. This type of hub is flying since 1974 and has been able to support a lot of evolutions and versions of Dauphin and Ecureuil families. It is presented the way to manage the composite material all over the years, the evolution of the certification process, the main difficulty encountered in service and the solution applied. A new Starflex® with a new resin epoxy and integrating all the improvements will be delivered to our customers before end of this year. For this new version the static and fatigue substantiation principles are given.

Notation

- AA: accelerated ageing
- A6: fatigue limit for 10^6 cycles
- H/C: Helicopter
- ILS: inter-laminar shear stress
- R: load ratio = minimum load / maximum load
- REACH: Registration Evaluation Authorization and restriction of Chemical substances
- S: applied load
- σR: ultimate strength

1. Introduction

The Starflex® is a Helicopter hub developed in the 70’s under the technical leadership of Mr René Mouille. It was at this time a great advanced technology. This hub in composite E glass fibre with an epoxy resin is composed of a few components. The simplicity, its low weight and costs are its major advantages. The hub itself has two areas, the thick part which carry all the main rotor loads (centrifugal loads, rotor mast bending moment, lift and main rotor torque) and the arm where the damper is fixed.

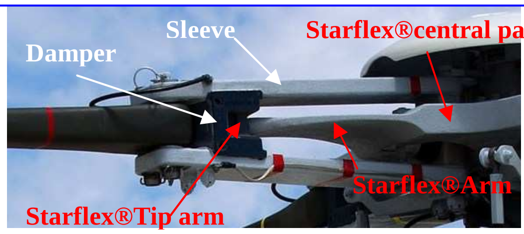


Figure 1: Starflex® hub

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The specificities of the Starflex® are:

- critical component,
- thick composite part (between minimum 8 mm for the arm up to 82 mm maximum for central part),
- high fatigue loaded component.

The way to substantiate was also innovative at this time. The thick part was substantiated in fatigue by a conventional safe life approach and the arm by an interval inspection based on a slow "flaw growth" concept which was quite new for composite structure.

The light Helicopter Ecureuil family and the medium Helicopter Dauphin family are equipped with this hub technology. The first certification of the Ecureuil (350 B) was end of 1977 and the first certification of the Dauphin (365 N) was in 1981. Today a service experience of more than 30 years is available. End of 2010, 5700 H/C have been manufactured (4900 Ecureuil and 800 Dauphin) and around 27 millions of flight hours have been performed. These helicopters are operated all over the world so under all the possible climates and environments, associated to a high diversity of missions.
All along the years many evolutions and new versions of Ecureuil and Dauphin have been developed; the main rotor torque, the weight and CG location, the operating domain, have been increased and a new airframe has been designed for EC130 Ecureuil.

2. The material change process

The material management is a key issue for composite regarding in particular the cost qualification (specific for the aeronautical field and amplified for critical parts) and the evolution of the material suppliers industry. It is a specificity of the composite due mainly to the complexity of the resin composed by numerous products and also probably to a lack of international standards. There are two aspects: the quality follow-up and the qualification of the material evolution. For both, Eurocopter methodology is based on two kinds of tests. First ones are sample tests (for mechanical characteristics as Young Modulus, static and fatigue strength) and second ones are tests, mainly fatigue tests on the real components. These second kind of tests could be only on the arm or both on the arm and on the central part. Depending of the case, sample tests or both sample and real components tests could be used.

Since the beginning of the Starflex®, a dedicated sample has been introduced for fatigue behaviour survey in addition to the standard samples for static strength. The thickness of this sample is higher than standards one in order to be close to the real part range. For each batch, fatigue tests are performed and a statistical criterion is applied for the batch acceptance. The experience has shown that this kind of test is very sensitive and highlights "little" modification of the material process, which are not detected by static tests. For instance, in 2002 the supplier impregnation line has moved, and the fatigue test has detected a decrease. Investigation led to the tooling which calibrates the resin (scraper). After the move the tooling position was slightly different, and the consequence was a possible deterioration of the fibre sizing. During this phase (up to the modification of the tooling position), fatigue tests were performed on Starflex® arms for the acceptance of each batch.

Another point to mention is the evolution of the material due to the suppliers. They are usually parts of important international group and their policy is changing all over the years. The following examples illustrate this concern:
- In 1993 the supplier of the plasticizer stopped the manufacturing so a new supplier had to be qualified,
- In 1997 due to the supplier new policy, a new supplier of plasticizer had to be qualified,
- In 2002 the impregnation line of the supplier was moved,
- In 2003 the fibre supplier stopped the manufacturing so a new supplier had to be qualified,
- In 2010 the fibre supplier stopped the manufacturing so a new supplier had to be qualified. This qualification has been linked to the new resin in this case (see paragraph 5 new Starflex®).

Depending on the case, tests on samples and on Starflex® arm were done for the qualification. Since a few years, the fatigue follow-up is done directly by the suppliers. It is an important improvement, suppliers are now more aware of the importance of fatigue behaviour.

3. Ageing effect

This effect was one of the most important issues for the first designers and certification team. At this time the key parameters were not well known and different simulations were done:
- Full scale components were subjected to real humid ageing for one year in France,
- Samples were tested in accelerated ageing conditions: a combination of submersion in water, ultraviolet rays and exposition to hot air (70°C).

Fatigue tests on the arms were performed and showed either no loss of strength (natural ageing) or improvement (accelerated ageing). The figure 2 gives the results.

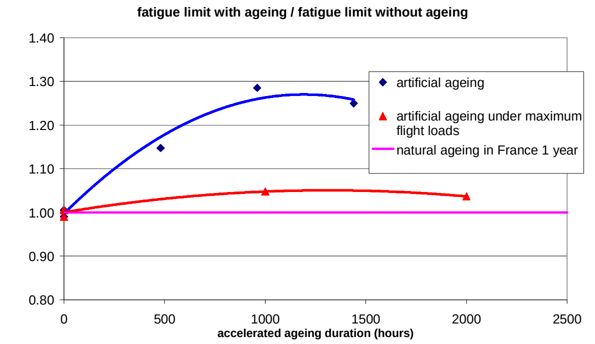


Figure 2: Influence of natural ageing and accelerated ageing on fatigue behaviour for real components

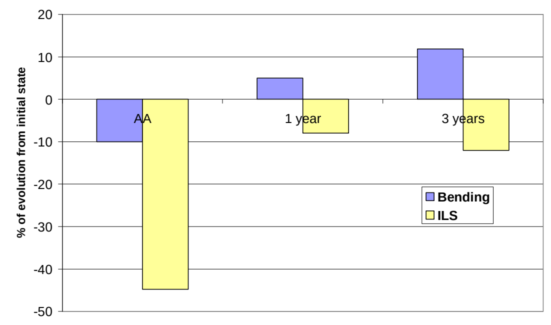


Figure 5: fatigue limit % of evolution from initial at 25°C (Sample results)

Later, some test specimens representative of the Starflex® arm in terms of thickness and material were naturally aged in the weather conditions of Pointe-à-Pitre (Caribbean Islands) for three years outside without painting protection. Fatigue and static tests were performed at 25°C in bending and inter-laminar shear stress (called ILS). The results were compared to the accelerated ageing conditions: 1000 hours at 70°C with 95% relative humidity (called AA). According to the scientific community the percentage of humidity absorbed is a good parameter for quantifying the ageing. The figures 3, 4 and 5 give the main results.

It appears clearly that the percentage of humidity absorbed in the case of accelerated ageing is much higher than the values obtained in natural ageing. The effect on static and fatigue behaviour is also quite different from the natural case.

Consequently, measurements on the fleet have been performed. There were focused on “old” Starflex operating in extreme environments in the world regarding the moisture effect. The figure 6 gives the synthesis and it is indicated the maximum and minimum values for each component (around 8 values per part).

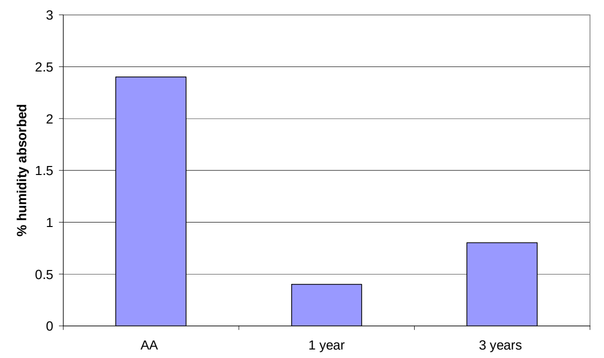


Figure 3: % of humidity absorbed on samples after natural ageing 1 year and 3 years and accelerated ageing (AA)

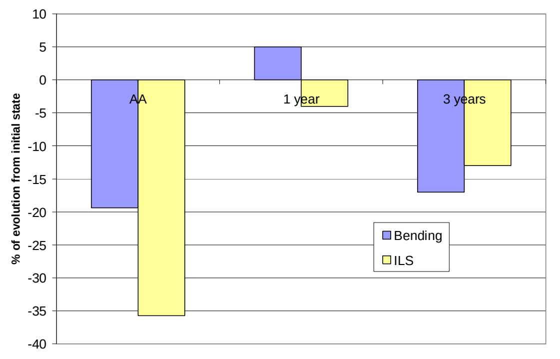


Figure 4: static strength % of evolution from initial at 25°C (Sample results)

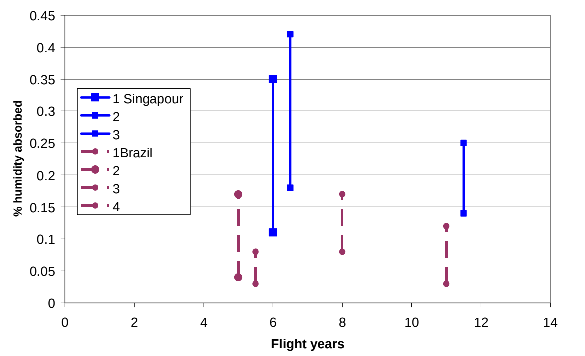


Figure 6: % humidity absorbed in Brazil and Singapore area Starflex® Measurements

It appears:

- the age is not a key factor,
- the location is important,
- the % of humidity absorbed is much lower than for sample in Pointe à Pitre (0.8 %).

The temperature effect on the static strength has to be considered and for Starflex® the maximum temperature in service was estimated to 50°C. Static tests have been done at 50°C after ageing corresponding to 0.8% humidity absorbed (value obtained after natural ageing in Pointe-à-Pitre).

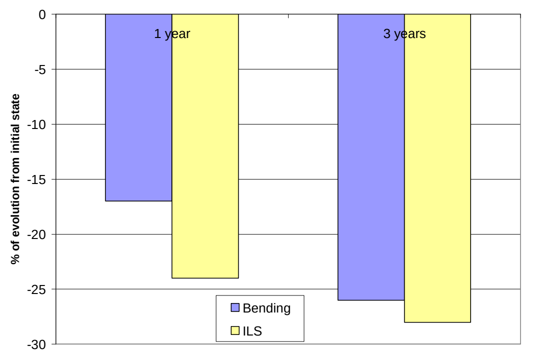


Figure 7: static strength % of evolution from initial at 50°C (Samples results)

In conclusion based on all the results, a knock down factor of 0.72 (-28%) was taken into account for static substantiation. For fatigue substantiation, ageing effect was considered negligible.

4. Damage tolerance

For the first certification no damage tolerance requirement existed, the studies for H/C rotating parts were focused on the fatigue behaviour and the ageing effects. The first requirements were coming from the well-known Advisory Circular AC 20-107 A. This AC highlights not only the effect of the ageing and the temperature but also:

- impacts effect,
- effect of the repeated loading on the static strength,
- damages coming during fabrication, assembly or in service,
- material variability,
- environmental effect on the flaw growth and the no-growth behaviour.

4.1 Impacts

The first difficulty was to define the right level of energy to apply (it should correspond to a realistic level and it is also called the energy cut-off).

It was based on the large Eurocopter experience available on impacts for metallic parts. During the overhauls of the mechanical component, measurements were performed. A relationship has been established between the impact depths and the impact energy. Under a Gauss distribution assumption, this study shows a mean energy around 11 joules associated to a standard deviation of 6.5 joules. The maximum energy derived is 26 Joules.

Note that the approach based on the metallic component has been also used in the fixed-wing aircraft [1]. The value of 48 joules maximum was obtained for the F15 wing. This value of 48 Joules seems consistent with the 26 Joules regarding the size and the tooling used for maintenance between a wing and a rotor hub.

For composite parts the experience of the Starflex itself does not permit to establish an energy value, due to the fact that no significant cases have been reported by our customers. In parallel for different H/C certifications or qualification and for other different composite components (as blades, transmission shafts), the value of 25 Joules was agreed. In [1] after a field survey, it is noticed that the value for fixed wing aircraft of 35 Joules was obtained for the A320 composite parts. For the same reasons than the F15 wing it seems consistent with 25 Joules for rotors.

The value retained for the Starflex® was 25 joules associated to an impact diameter of 25.4 mm. This diameter was chosen rather than a lower one because it is severe in terms of damages and visual detection.

The first certification was done as follow:

- real parts have been impacted at 5, 15, 25 joules and some at 30 joules. The goals were to quantify the damages created and whether they are visible or not. Tests under 30 joules were done in order to check that there is no threshold effect,
- fatigue tests on samples representative of the real damages have been realised.

No significant degradations are observed on the faces whatever the area.

For the edges of the central part, small local surface degradations are created and the composite is locally crushed. These degradations are clearly visible. The fatigue and static samples give a knockdown factor of 0.89. The substantiation was done based on this factor applied on the fatigue and static tests results.

For the edge of the arm, the degradations are bigger and delaminations are created (figure 8). This type of damage is covered by the flaw growth approach explained later.

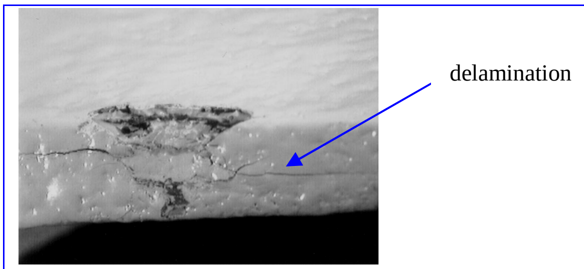


Figure 8: after impacts of 25 Joules (on the arm edge)

4.2 Effect of the repeated loading on the static strength

It is not the main concern for rotors parts. In fact usually fatigue tests are done applying factors on the loads until damages, degradations or loss of stiffness appears. The main goal is to have the fatigue limit.
Therefore in a first step the principle was to quantify the effect using samples. The figure 9 gives the results for the minimum values obtained (2 material batches have been tested):
- 10^6 cycles are done for two ratios σmin/σmax, 0.6 and 0.9,
- A6 is the fatigue limit for 10^6 cycles,
- S is the load level applied before the static test,
- S/A6 is the percentage of the fatigue limit applied.

Knowing that the fatigue loading of the Starflex® is close to S/A6 = 0.6, a decrease of 10% of the static strength has been deduced (knock down factor of 0.9). For the last certifications, a static test after fatigue test was done. As it was performed after the fatigue test dedicated to fatigue substantiation, therefore with amplified loads close to the fatigue limit, it is a severe way (see curve figure 9; the knock down factor is in this case probably around 0.7 to 0.8).

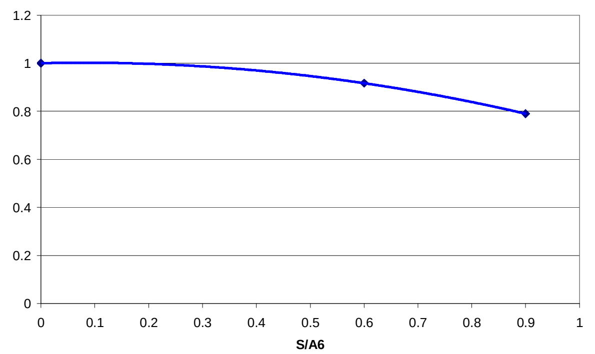


Figure 9: relative residual static strength after fatigue - knockdown factor

4.3 Damages coming from fabrication, assembly and in service

It was shown that the most critical damages are those coming from impacts (25 Joules) and delaminations. Delaminations are initiated either by impacts, or by fatigue at the edges of the arm (see the flaw growth approach explained later).

4.4 Material variability

For each material, static tests are done and are parts of the acceptance criteria. The variability coefficient for the Starflex® is lower than 5%, based on data covering more than 15 years. A safe value is derived ("A" value).
This "A" value has only been used in case of substantiation by analysis. In case of full-scale tests for which impacts, fatigue, ageing and temperature have been applied, this factor was not taken into account. The rational is:

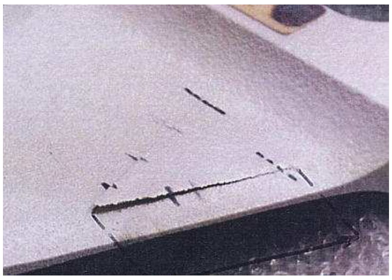
- the major effects are ageing, temperature and damages (impacts, fabrication damages),
- the fatigue effect is introduced in the tests in a severe way (with amplified loads refer to paragraph 4.2),
- there is no cumulative effect of the different parameters. For instance, residual static strength tests have been done for two different batches (§ 4.2) and results are given in the table below.

	Batch A	Batch B
σR (mean)	1	1.02
Fatigue limit (mean) A6	1	1.03
Static after fatigue S/A6=0.6	1	0.976
Static after fatigue S/A6=0.9	1	0.989

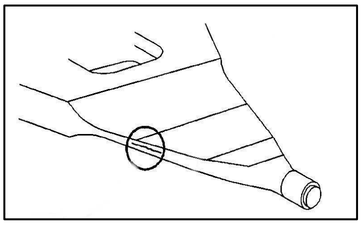
In this case there is a relationship between the static strength capability and the fatigue limit, but the fatigue effect on the residual static strength is different. Therefore it is underlined that cumulative effect is not representative of the real effect.

4.5 Flaw growth substantiation of the arm

The substantiation with a flaw growth concept is a specificity of the Starflex® arm. Even today in the aeronautical field this principle is often considered as not practicable. As it is said in [1] "the no-growth concept would be the foundation of the damage tolerance".
A remark has to be mentioned concerning the Starflex arm: the main loads are carried by the sleeves to the Starflex® central part through the spherical bearing, so the arm failure has not a catastrophic effect upon the aircraft.
The important experience on the Starflex demonstrates that the flaw growth concept could be applicable.
The demonstration was done through full-scale tests for which the purpose is to quantify the flaw propagation rate (see figure 10).



Splinters



delamination

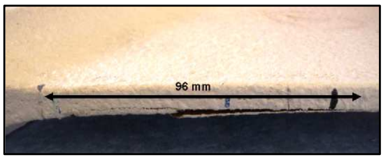


Figure 10 example of damages obtained during fatigue tests

Propagation tests have been done through dedicated samples, so called TCT-specimen (transverse crack tensile) which have been used for blades purposes (glass fibre) [2] but also for carbon [3]. The principle is given in figure 11.

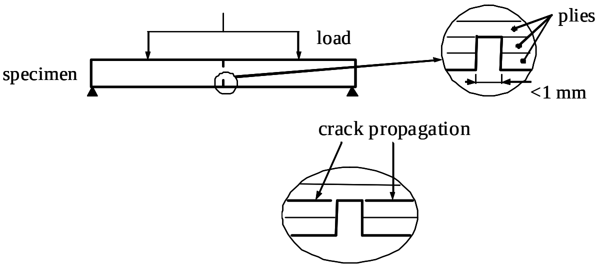


Figure 11: propagation tests samples

Different parameters have been studied:
- ageing,
- load ratio R = Fmin/Fmax (0.1 and 0.8),
- temperature: 21°C, 35°C, -40°C.

The main results are given in figure 12 for ratio R=0.8. The ageing effect is low and beneficial (in case of test at room temperature the ageing effect is 3%). Hot temperature is also beneficial for the propagation. The cold temperature is the most critical case. Consequently, for the substantiation of the arm interval inspection, a factor of 1.55 on the number of cycles has been used.

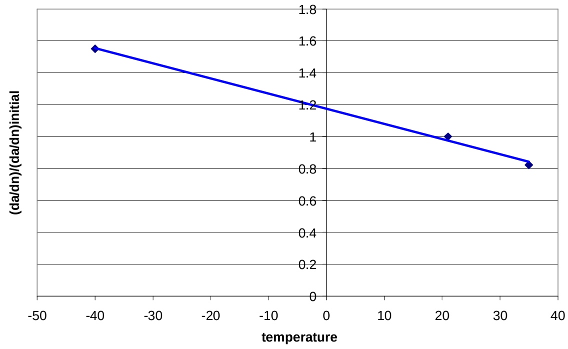


Figure 12: Relative flaw growth propagation on samples

5. Difficulty encountered in service and the solution

No serious incidents have been reported on the Starflex®, except two cases concerning the tip arm.

These incidents occurred in 2005. It was quite surprising that it has appeared after an important number of flight hours. The first one occurred on an Ecureuil: the tip arm was presented an important deformation (figure 13). The second one happened a few months after on a DAUPHIN: the tip arm has been broken and the pilot has been able to land (figure 14).

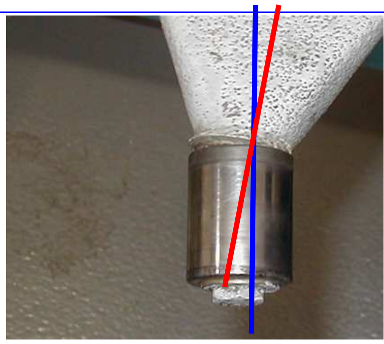


Figure 13: ECUREUIL Tip arm deformation

Figure 14: DAUPHIN tip arm failure

Flight tests, laboratory tests, and investigations have been done and have shown that under certain circumstances the composite temperature could locally exceed the glass transition temperature. This effect is mainly due to the warm up induced by the ball bearing dynamic movement and the friction coefficient associated. It is explained in case of high external temperature associated to high speed conditions and also by the ball bearing dispersion (gap, wear, friction coefficient…). Before these incidents, such level of temperature increase was not expected.
Design modifications have been done but the most important improvement was to drill holes in the main rotor damper in order to cool the confined area of the tip. A visual interval inspection has been put. Another improvement is done through the new Starflex® version presented in paragraph 6.

6. The New Starflex®

6.1 The new resin

These new Starflex® (Dauphin and Ecureuil) are based on a new resin epoxy. This new resin free of solvent is answering to the REACH requirements. In addition as presented in the paragraph 2 the current fiber supplier will stop its production, so the qualification concerns the resin and the new fibre supplier.

This new resin provides major improvements:
- additional temperature margin for the tip arm,
- excellent behaviour after ageing particularly for the inter-laminar shear stress,
- fatigue limit increase in bending.

6.2 The certification process

The first point was the material evaluation and qualification. A complete test campaign on samples has been performed. For ageing it has been considered the maximum percentage of humidity absorbed by the current material (see paragraph 3) knowing that the new resin retains less humidity.

Three different areas were considered for the certification process:
- the central part,
- the arm,
- the tip arm.

Hereafter is detailed the Ecureuil case.

For the central part the certification tests were done following the sequences described below:
- impacts of 25 joules on the critical areas; the damage created is more critical than the minimum manufacturing quality,
- fatigue tests: the test was conducted with amplified loads in order to demonstrate a safe life; it gives the service life limitation,
- static tests up to ultimate load with increased coefficient coming from ageing; the effect of the fatigue is integrated in a severe way due to the increased loads (see paragraph 4.2). It demonstrates the ultimate margins.

For the arm first kind of test:
- impacts of 25 joules on the edge,
- fatigue tests to create a first delamination (more severe than the minimum manufacturing quality); see test bench on figure 15,
- static test until failure and ultimate margin substantiation taking into account the ageing and temperature effects by the coefficients issued from samples.

For the arm second kind of test:
- impacts of 25 joules on the edge,
- fatigue tests until delamination,
- crack growth propagation for interval inspection substantiation,
- static test until failure and limit margin substantiation taking into account the ageing and temperature effects by the coefficients issued from samples.

For the tip arm
- simulation of a de-bonding covering the minimum manufacturing quality,
- fatigue until damage initiation : under the maximum flight load and with a temperature spectrum,
- accelerated ageing in a large climatic chamber,
- static test until failure and ultimate margins substantiation at the max temperature + 30°C.


Figure 15: Starflex® arm test bench

6.3 Main results

The service life limit is significantly increased and is depending of the versions of the Ecureuil and Dauphin families. The interval inspection is increased also for all the versions in a large way (at least a factor of 3). Another important point is the reliability which is expected to be much better.

7. Conclusion

Starflex® technology has been able to perform evolution during 40 years.
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 as:
- material evolution,
- new versions of Helicopters with increased flight domain,
- in service experience,
- new or evolution of the regulation rules (e.g REACH).

All these improvements have been done with always the goal to increase the safety level, the reliability and the performances. Two domains have to be mentioned:
- material: composite material requires a specific quality follow-up especially for parts submitted to fatigue,
- certification process: The large experience on the Starflex® has permitted to adapt the certification process at different levels: environment, damages, test procedure.

The new starflex® associated to the new resin is an important step and this composite hub will continue to be a challenging technology.

Figure 16: Starflex® on the Dauphin

8. References

[1] J.Rouchon NLR "Fatigue and Damage Tolerance Evaluation of Structures: the Composite Material Response" 25th symposium of the international committee on aeronautical Fatigue 27 may 2009 Rotterdam

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