19th European Rotorcraft Forum

Paper N4

# Damage-Tolerant Tail Rotor Blade for AS 332 L2 Super Puma Helicopter

P. Rauch and A. Charreyre

*Eurocopter France*

September 14-16, 1993
Cernobbio (Como), Italy

Associazione Industrie Aerospaziali
Associazione Italiana di Aeronautica ed Astronautica

## Damage-Tolerant Tail Rotor Blade for AS 332 L2 Super Puma Helicopter

Patrice Rauch and Alain Charreyre
*Blade Design and Stress Department*
*Eurocopter France*

## Abstract

The design of helicopter rotor blades exposed to severe environmental conditions (impact, lightning, temperature, humidity, etc.) must be mastered to improve their operational safety and reliability. Civil regulations are changing, and certification of composite blades now requires them to meet damage tolerance requirements. Furthermore, the special "*no catastrophic consequences after a 100 g metal body impact*" condition imposed by the French authorities (DGAC) for the recent certification of the new AS 332 L2 helicopter's tail rotor blades illustrates the challenges that manufacturers will face in the near future.

Although overall damage tolerance is not required for certification of the AS 332 L2 helicopter dynamic components, Eurocopter France adopted this approach from the beginning of the tail rotor blade development phase.

This paper reviews the major stages of the blade design process:

- identification of potential aggression;
- examination of stress paths;
- failure mode analysis;
- selection of suitable damage-tolerant technologies;
- simulated impact;
- fatigue qualification tests and/or methods.

## 1. Introduction

The AS 332 L2 *Super Puma* helicopter shown in Figure 1 is a significant evolution from the existing version, and most of the major subassemblies have been modified. Rather than upgrading the existing tail rotor, it was decided to develop a totally new one in order to achieve a significant step forward with regard to performance, damage tolerance, maintenance cost and operational reliability. To meet these objectives, a four-bladed soft in-plane *SpheriFlex* rotor was selected with a conical integrated mast-hub unit and fork-mounted blades.

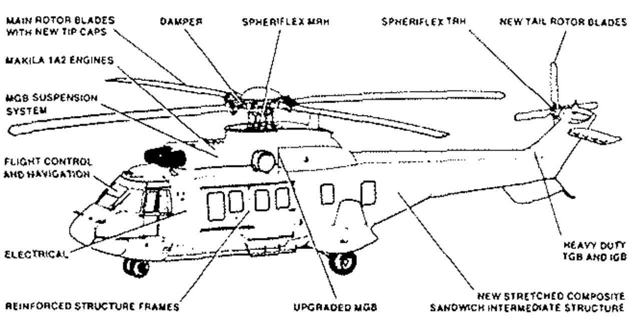



Figure 1. Some redesigned items on the new *Super Puma*

The AS 332 L2 tail rotor blade design is based on over two decades of experience with composite materials for rotor blades and other major helicopter components. Over 45 000 composite blades have been produced to date for five different types of aircraft, and have logged over 52 million hours of flight under a wide range of environmental conditions with operators in 119 countries.

Eurocopter France (ECF) has thus acquired unequaled knowledge of the behavior of these vital components in operation. Numerous incidents without serious consequences have been logged by civil and military operators, notably with regard to the damage tolerance of composite rotor blades. This body of experience has confirmed the fail-safe and damage-tolerant character of the blade design. The impact strength of these blades is illustrated by three recent examples involving civil aircraft:

- An *AStar* main rotor blade severed a shielded cable 50 mm thick on a 225 000 volt power line while engaged in fighting a violent blaze (Figure 2).

Figure 2. High wire impact

- A *Dauphin* flew for one hour off-shore with the skin of the main rotor blades ripped open by the hoist cable which accidentally struck the rotor. The role of the crack arrester ribs on the blades is clearly illustrated in Figure 3.

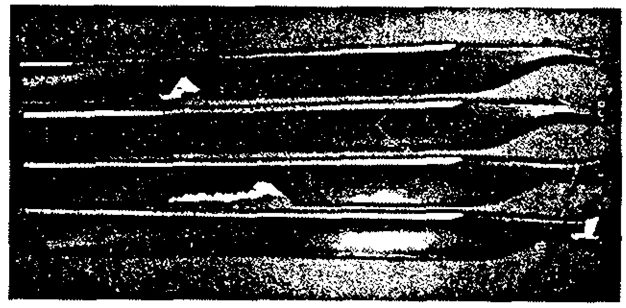


Figure 3. Crack arrester ribs

- *Super Puma* blades fitted to an all-weather aircraft have demonstrated damage tolerance on several occasions, for example by their excellent response to lightning strikes in flight (Table 1).

| | | |
|---|---|---|
| EVENTS IN USE | 48 | AIRCRAFTS struck by lightning ⇓ |
| | 91 | MAIN BLADES struck |
| CONSEQUENCES | | { 7 blades rejected; 84 blades restored to flight |
| SECURITY AVAILABILITY | | No accident |

Table 1. Lightning strikes on ECF heavy helicopters main rotor blades (1983 - 1993)

The in-service behavior illustrated by these examples must not overshadow the fact that helicopter operating conditions are extremely severe (normal and low-altitude flight, ground operation, etc.) and that the development of any new component must implement the best available materials and technologies to further enhance operational safety. This is especially true for conventional tail rotors which according to US Army statistics[1] are responsible for 20% of the serious accidents that occurred between 1978 and 1988. Of these accidents, 39% were due to tail rotor strikes (ground, object, tree); this represents an accident rate of $2.9 \times 10^{-6}$ per hour of flight (Figure 4).

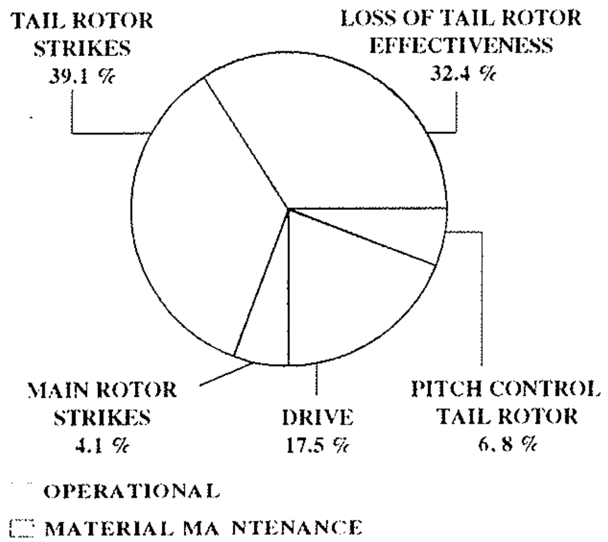



Figure 4.
Summary of US Army tail rotor mishaps (1978-1988)

This analysis is consistent with ECF statistical investigations showing that helicopters equipped with conventional tail rotors are more exposed to accidents than *Gazelle* and *Dauphin* helicopters implementing the shrouded tail rotor concept[2]. Nevertheless, with its unusually high ground clearance, the *Super Puma*'s conventional tail rotor has a strike accident rate only half that of the *AStar-TwinStar* or *Alouette* light helicopters.

Figure 5 shows the tail rotor strike rate observed for the *Puma* and *Super Puma* helicopters. Damage related to impact by solid objects - most often detached from the aircraft itself - is the most frequent. Although the overall occurrence rate is less than $10^{-6}$ per hour of flight, they have in some cases resulted in severe accidents. This type of accident may also occur during sling operations if the cable or the load strikes the blades. Rotor strikes on the ground generally involve maintenance tools or access ladders.

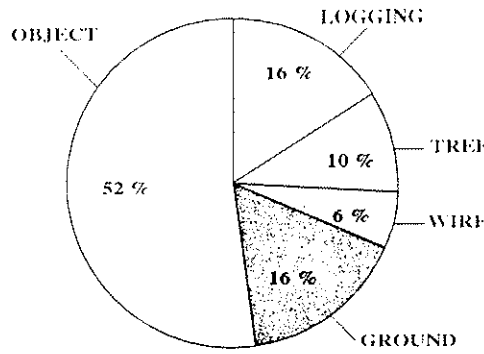



Figure 5.
Tail rotor strike rate on heavy helicopters (ECF data base)

ECF, in conjunction with the DGAC, therefore made improving accident safety one of the main objectives of the new AS 332 L2 tail rotor blade design program. Concretly, the DGAC issued a special certification requirement supplementing the criteria specified by FAR 29. The French authorities require an experimental demonstration to prove the helicopter can fly safely for 30 minutes after a frontal impact on the blade by a 1.8 kg bird in level flight at the horizontal speed $V_H$, or by a 100 g metal object with no relative velocity with respect to the helicopter.

To meet these demonstrated safety objectives, and although the AS 332 L2 dynamic components are not required to meet overall damage tolerance certification, ECF decided to adopt a damage tolerance approach from the beginning of the tail rotor development work.

## 2. Damage Tolerance Principles Applied to Composite Blades

### 2.1 General

The underlying philosophy is expressed in AC 29571 :

*"The service life of critical components shall be determined. Moreover, an assessment of the structure fatigue strength with allowance for fault tolerance shall ensure that even in the event of manufacturing or operational defects, the structure will withstand operating loads without failure until the defective part is replaced or the defects (including the resulting fatigue cracks) have been detected or repaired. Either type of fatigue strength assessment may be used to substantiate damage tolerance: i.e. the flaw-tolerant safe life method or the crack growth method."*

The new requirement meets two needs:

- It eliminates parts that are overly sensitive to manufacturing defects or to flaws induced during maintenance operations: the fault criticality of these parts is not necessarily detected by the "safe life" approach.

- It sets up an inspection program based on damage allowance (impact damage, environmental damage, fatigue damage, etc.).

ECF developed the "damage tolerance" philosophy as early as 1974 - well before the regulatory demands - in the *StarFlex* rotor arm, which meets major flight safety growth requirements by virtue of fail-safe component design and the use of materials with slow damage propagation detectable by simple visual inspection (Figure 6).

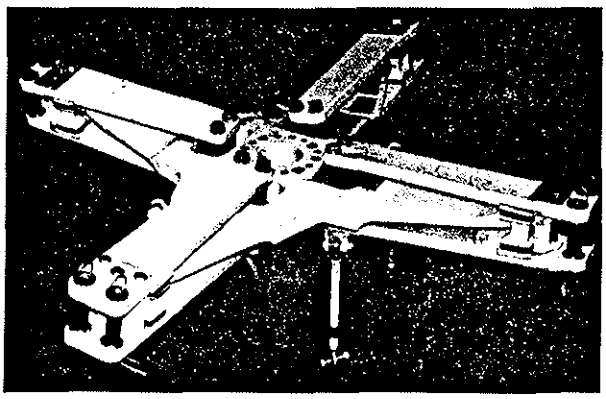


Figure 6. *StarFlex* main rotor head

## 2.2 Substantiation Principles

### 2.2.1 Failure Modes, Effects and Criticality Analysis (FMECA)

Each part of the blade was investigated rationally and systematically to define:

- failure modes: rupture, debonding, etc.
- possible causes of failure: fatigue stresses, impact, environment, etc.
- failure occurrence probabilities
- failure consequences on the blade and on the helicopter.

An occurrence probability of less than $10^{-9}$ per hour of flight must be demonstrated for a fatigue-stressed blade whose failure (e.g. failure of an attachment winding) would lead to a catastrophic accident or immediate landing. As regards the possible causes of failure identified above, the same occurrence probability ($< 10^{-9}$) must also be substantiated for the specified periodic inspection interval.

In compliance with the FMECA analysis results, the blade fatigue substantiation rules and the provisional maintenance plan were developed as outlined in Figure 7.

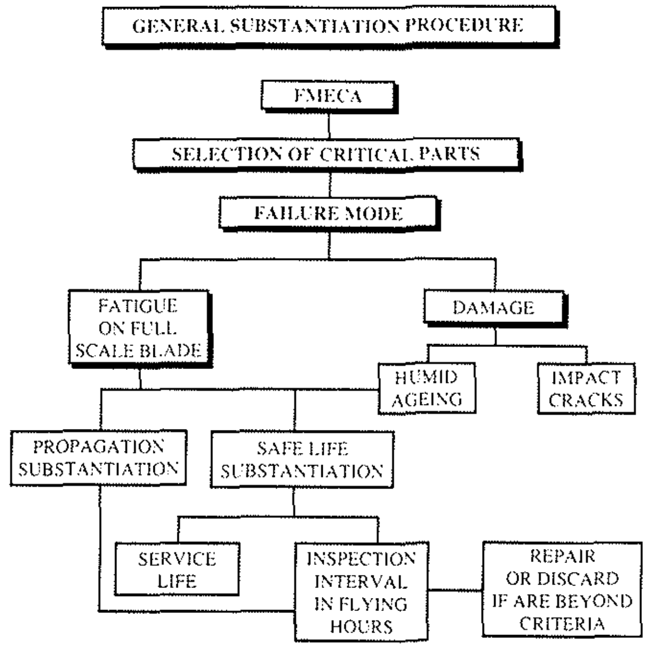



Figure 7. Substantiation procedure

### 2.2.2 Fatigue Damage Substantiation

Fatigue substantiation of undamaged blades is based on the conventional "safe-life" procedure (Figure 8), from which a service life is determined from the following:

- fatigue strength demonstrated by testing of 4-6 components
- fatigue working curve based on a cumulative probability of $10^{-6}$
- a flight-measured load spectrum
- Miner's linear cumulative damage law.

SAFE LIFE SUBSTANTIATION
DETERMINING THE SERVICE LIFE

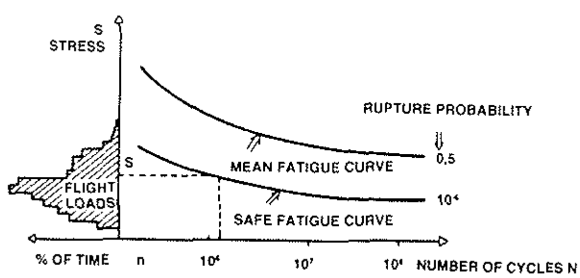



Figure 8. Conventional safe-life procedure

#### 2.2.3 Discrete Damage Substantiation: Impact, Crack, Lightning

Fatigue substantiation of damaged blades is based on propagation tests with previously damaged blade in the most heavily loaded areas. The approach adopted for the tail rotor blades was to assume a damage occurrence probability of $10^{-3}$ in a critical zone, and to substantiate the non-propagation of the defect with a probability of $10^{-6}$ in order to ensure a risk of less than $10^{-9}$ per hour of flight.

Tests were conducted at 1.35 times the maximum in-flight dynamic loads. This multiplier factor covers non-propagation scattering for composite materials, and was based on an investigation of propagation curves, propagation threshold and the $G_{Ic}$ and $G_{IIc}$ values scattering for the materials used: glass, carbon fiber and resin (Figure 9).

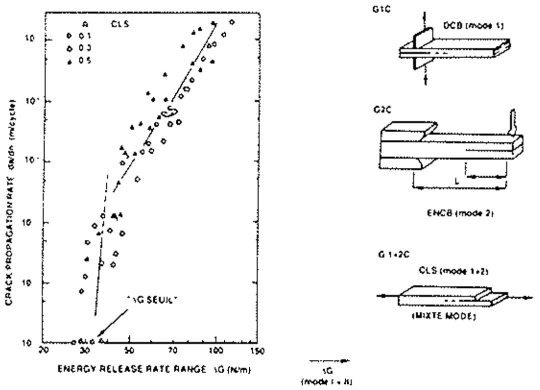



Figure 9. Propagation analysis

## 2.3 Tail Rotor Blade Damage Allowance

Damage tolerance requires exhaustive prior analysis of all possible damage. Four general damage classes may be defined:

- Fatigue damage
- Environmental damage (temperature, humidity, ageing)
- Inherent manufacturing defects
- Discrete damage.

### 2.3.1 Fatigue Damage

Fatigue is the primary phenomenon for rotor blades, particularly as they do not present in general multiple load paths by design. The new certification requirement adds allowance for defects relative to undamaged parts, but does not suppress the safe life approach.

Fatigue substantiation of the blades was based on the service life concept. Fatigue failure would result in a catastrophic accident, and an occurrence probability of less than $10^{-9}$ per hour of flight must be substantiated (refer to § 2.2.1 and 2.2.2).

### 2.3.2 Environmental Damage

AC 29571 refers to AC 20107 with regard to composite materials. Ageing and temperature effects on tail rotor blades were taken into account by testing of material specimens in environmental conditions corresponding to an aircraft operating temperature range extending from -45°C to +50°C. It was therefore considered necessary to allow for potentially high temperature conditions with the rotor stopped and the aircraft parked: it must be demonstrated that high-temperature creep does not occur under these conditions.

### 2.3.3 Inherent Manufacturing Defects

The type and size of the defects to be taken into account were determined on the basis of experience with blades in service, and after manufacturing the first parts. The size corresponds either to the detection threshold of existing non-destructive test facilities (X ray, holography, etc.) or to the size of the largest defect determined from the manufacturing process ( incorrect cut-out, missing ply, inverted lay-up).

### 2.3.4 Discrete Damage

#### 2.3.4.1 Tail Rotor Strike

The study referred to in Figure 5 also discriminated between two types of blade damage: lateral impact on the skin, or frontal impact on the leading edge.

- In the event of a lateral impact, the principles of composite blade construction involve thin skin (0.7-1.3 mm thick for the AS 332 L2 tail rotor blade) offering a low resistance to perforation: the energy necessary to create notch damage is low (on the order of 10 $J \cdot cm^{-2}$ for the blade skin). It was assumed that the skin perforation threshold would be reached in any case of impact, and that the defect would be detectable by visual means (VID: visual impact damage). The approach then consisted in ensuring that flight safety was not jeopardized by these skin perforations. For this reason, a non-propagation demonstration was proposed for more severe fatigue crack-initiated damage (refer to § 4.2.2.2).
- The impact of a solid body in compliance with the DGAC special requirement is tested frontally.

#### 2.3.4.2 Bird Strike

Recent statistics [3] compiled by the RNLAF (Royal Netherland Air Force) surprisingly show high bird strike rates in comparison with the civil statistics used to date : they indicate a global impact risk on the order of $10^{-6}$.

The operating experience with the *Puma* and *Super Puma* has not uncovered any serious incidents following a bird strike. However, a demonstration test was therefore conducted on the AS 332 L2 tail rotor blades with a 1.8 kg bird.

#### 2.3.4.3 Lightning Strike

The requirements for lightning strikes are defined by applicable standards (AC-20-53A). The estimated occurrence probability for this type of lightning strike has been estimated to be less than $10^{-4}$; a conservative value of $10^{-3}$ was used in this case.

#### 2.3.4.4 Ice Lump Strike

To obtain CAA limited icing clearance, an investigation of the trajectories of ice lumps likely to impact the tail rotor blades led to consider two types of impact.

Frontal impact of an ice lump weighing 300 g detached from the structure or from the main rotor hub is highly likely, and has been observed in flight; such impacts were simulated in the laboratory.

Lateral impact of elongated ice lumps weighing 100 g accreted on the main rotor blade leading edge has a very low occurrence rate; the impact would perforate the blade skin, and non-propagation of the damage is demonstrated in the same way as indicated in § 4.2.2.2.

## 3. BLADE TECHNOLOGICAL OPTIONS

### 3.1 Advantages of the *SpheriFlex* Rotor Head Design

SPHERIFLEX TAIL ROTOR HEAD

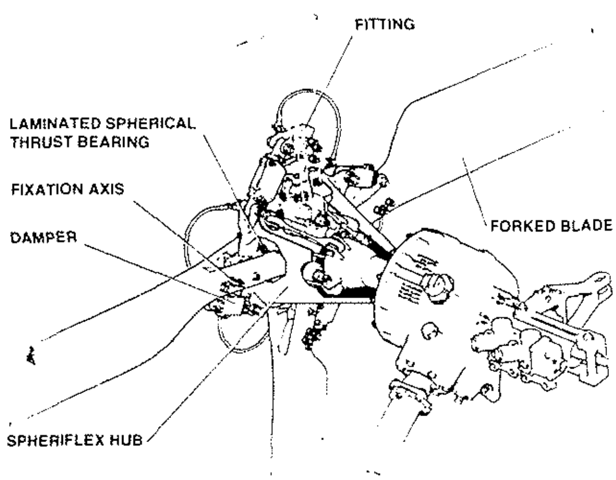



Figure 10. SpheriFlex tail rotor head

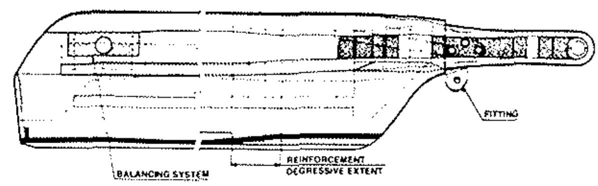
The *SpheriFlex* rotor head concept (Figure 10) provides for a compact hub assembly; two blade arms are attached to the spherical thrust bearing which is itself mounted on the hub. The two blade arms converge to form the aerodynamic main blade section.

In addition to its compact design, this fork technology also eliminates the additional assembly and connections that would be required with a hub sleeve, and thus enhances reliability. By allowing the blade arms to enter the rotor head, this solution also provides greater protection of the sensitive blade attachment points.

Finally, the fork design houses and protects the drag damper attachment fitting, which reinforces the arms and contributes to the strength of the second critical blade zone: the fork root. This Y-shaped transition zone is reinforced by additional fabric plies, ribs and skin doublers; the double arm constitutes a strong load-supporting structure that nevertheless exhibits some flexibility.

The main section, with its optimized evolving airfoil design, is located beyond the reinforced zone and terminates in a parabolic blade tip.

FORKED BLADES - TECHNOLOGY




CURRENT SECTION

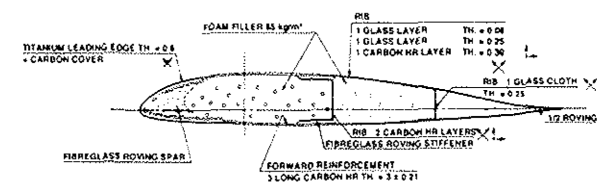


Figure 11. Forked blade technology

### 3.2 Main Section : Technology and Materials

The principal improvements over the original 332 L1 blade design that were tested and qualified on material test coupons, component subassemblies and on the complete tail rotor blade include the following:

- A three-box structure with a reinforced main-box, which also includes two rear spar flanges that terminate the unidirectional glass roving in the main section. These two flanges, which support the main-box rib, serve as crack arresters or crack propagation retarders.
- A mixed glass/carbon fabric skin laid up at ± 45°, and reinforced along the leading edge by unidirectional carbon tape plies. A more tolerant carbon fiber (High modulus ⇒ High Strength) was used and the leading edge lay-up sequence was optimized to minimize the effects of a perforating impact, even at low energies.

• Higher-density polyurethane foam cores ($50 \Rightarrow 65$ kg·m$^{-3}$) with higher compression and shear strengths, and which improve the overall structural behavior with regard to the initiation and propagation of debonding.

• Unidirectional glass tape along the trailing edge to limit any opening that could occur in this area.

A longer blade chord (+ 25%) for reasons of aerodynamic efficiency also allows higher stiffnesses and a more massive leading edge to withstand frontal impacts.

## 3.3 Blade Root: Technology and Materials

The fork concept is based on proven technology, implementing a unidirectional glass roving spar forming a winding around a metal bushing at the attachment points. The spar then merges smoothly with the blade profile to form the massive leading edge portion and the spar flanges.

The windings are reinforced by a thick layer of carbon fabric plies to ensure structural continuity between the skin and the transition zone at the junction with the two arms. The overall cohesion is enhanced by a series of ribs, which play a major role in ensuring damage tolerance in this zone.

ARMS & TRANSITION DETAILS

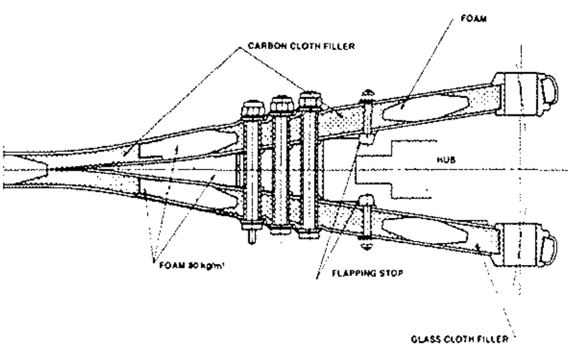



Figure 12. Arms and transition zone

## 3.4 Materials

All the blade materials are subject to stringent quality assurance procedures, and considerable expertise has been achieved in implementing them for blade molding. They exhibit satisfactory ageing performance even at high humidity and temperatures with respect to the demonstrated test coupon behavior used for blade *substantiation.*

In addition to structural strength and load transfer among sub-components, the final blade architecture and materials were determined to ensure satisfactory dynamic behavior while ensuring minimum blade weight.

## 4. BLADE STRENGTH AND DAMAGE TOLERANCE DEMONSTRATION

Substantiation of the blade and its behavior in the event of damage was confirmed with regard to previously identified damage. This approach assumes a number of elementary tests, notably on specimens representative of technological subassemblies. These tests form a pyramidal hierarchy (Figure 13) ranging from basic characterization of healthy and damaged material test coupons, to tests on complete blades with molding defects or damage resulting from external aggression.

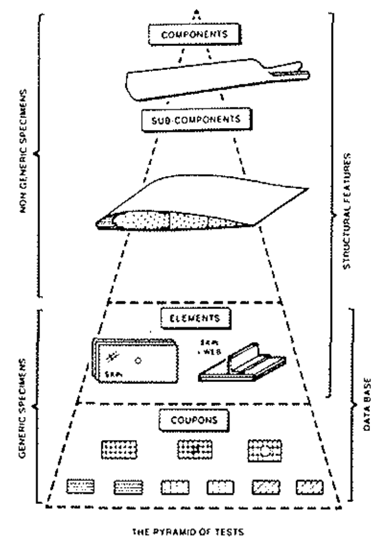



Figure 13. Test "pyramid"

## 4.1 Substantiation with Generic Specimens

### 4.1.1 Material Characterization

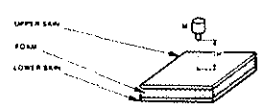
**SOLID BODY SKIN IMPACT**
**AS 332 L2 TAIL ROTOR BLADES**

**SUBSTANTIATION**

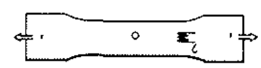
LATERAL IMPACT :

**The origin of skin impacts is very miscelaneous.**
**Choice of approach on test-sample then on test-part**

***TEST-SAMPLE REPRESENTATIVE OF SKIN BLADES**




**- Impactor**
**- Look for energy of impact for default :**
• No perforating
• Perforating



**- Static & fatigue test**

Figure 14. Characterization tests

Carbon fabric were selected rather than crossed tapes because the damage after impact is more limited and homogeneous around the perforation — notably on the thin skin in the main blade section.

Unidirectional carbon tapes were added on the leading edge for dynamic adaptation purposes. The skin ply lay-up sequence was optimized to minimize the consequences of impact.

Tests with healthy and impacted specimens provided quantitative data on the static and fatigue effects of impact (Figure 14). The following table 2 indicates the impact elongation coefficients determined for the leading edge and trailing edge structures.

| Leading Edge | Trailing Edge |
|---|---|
| 0° structure chief orientation | ± 45° structure |
| Linear overall behavior | Nonlinear behavior |
| $K_{impact} = 1.14$ | $K_{impact} = 1.44$ |

Table 2. **IMPACT COEFFICIENTS**

#### 4.1.2 Substantiation on Subassembly Components with Ribs

In addition to the demonstration of the role of the UD glass ribs and spars in service on Dauphin N main rotor blades as described in the Introduction, fatigue tests conducted on test coupons demonstrated their ability to deviate or retard crack propagation.

**PART OF RIB AND BEAM**

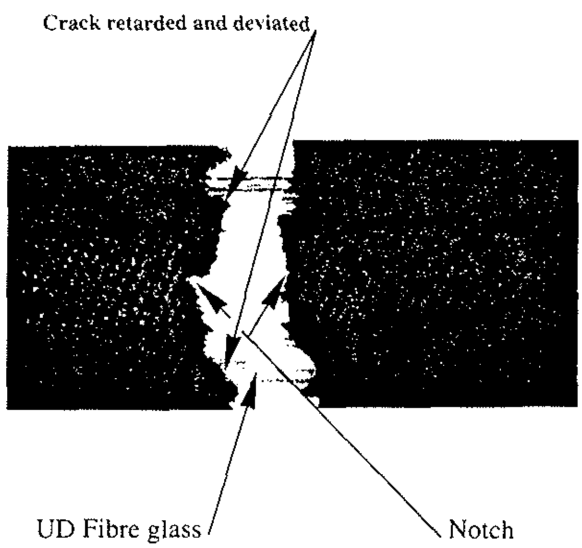



Figure 15. Role of the ribs and spars

Following analysis and interpretation of the results of simple loading tests on these specimens, a program was undertaken to substantiate all the types of damage and inherent manufacturing defects.

## 4.2 Rotor Blade Substantiation Tests

The comprehensive program ranged from conventional safe life limit tests to damage propagation tests. All critical blade zones were tested.

Four types of tests were conducted:

- Testing of the fork arms, notably the windings.

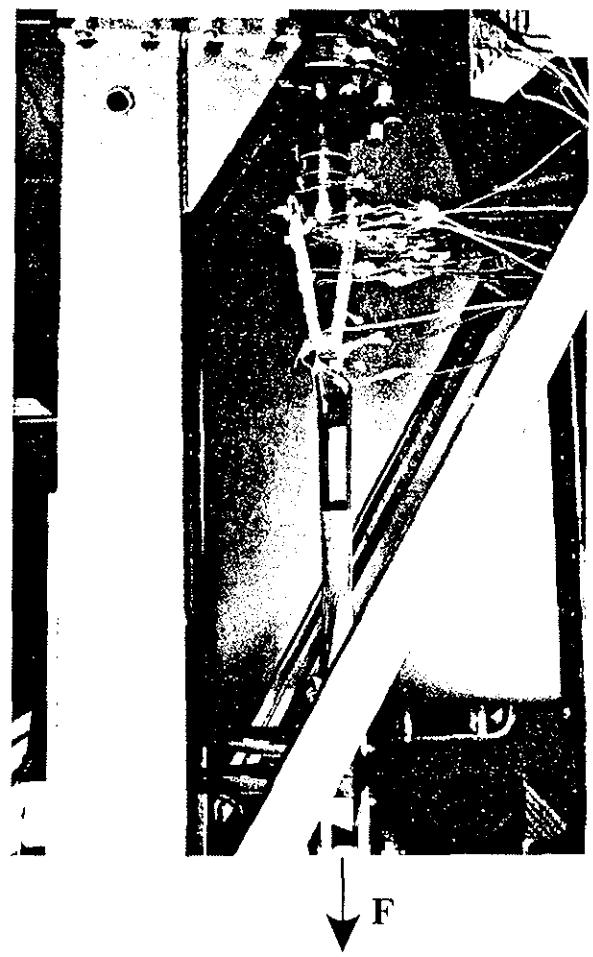



Figure 16. Blade attachment test configuration

- Testing of the transition zone.
- Additional testing in this zone of the assembly with the drag adapter attachment fitting.
- Testing of the main blade section.

#### 4.2.1 Conventional Tests

Simplified loading was used together with strain analysis for testing of the attachment zone (windings) and of the drag damper attachment fitting assembly zone.

The transition zone and main blade section were tested in such a way as to reproduce the complex loading sustained by the blade: i.e. centrifugal loading, flapping and drag flexures, and torsional loading.

### 4.2.2 Damage Tolerance Tests

#### 4.2.2.1 Blade attachment zone

As noted above, the blade attachment zone is protected inside the rotor head. Possible damage other than fatigue may be due to manufacturing defects or to lightning. Examinations following the lightning test at the CEAT facility showed no effects whatsoever on the attach winding (ECF experience with the 332 L1 includes no record of any damage to the attach windings after a lightning strike).

A full series of tests were conducted on parts with intentional molding defects: undulations adjacent to the attach windings, missing interface ply between the roving and the bushing, or improper bushing cut-out.

The only significant effect was observed in the case of undulations directly affecting the unidirectional glass material: a 15% drop in the fatigue limit was noted for moderate undulations, rising to 30% for severe undulations. In order to prevent this type of defect, the production blade was designed with precured internal root reinforcements to prevent any risk of undulation during molding or when the resin is in a liquid state.

Ageing was taken into consideration on elementary test specimens. The results showed no drop-off in the material fatigue performance for the epoxy-impregnated unidirectional glass material constituting the spar.

#### 4.2.2.2 Transition and aerodynamic section areas

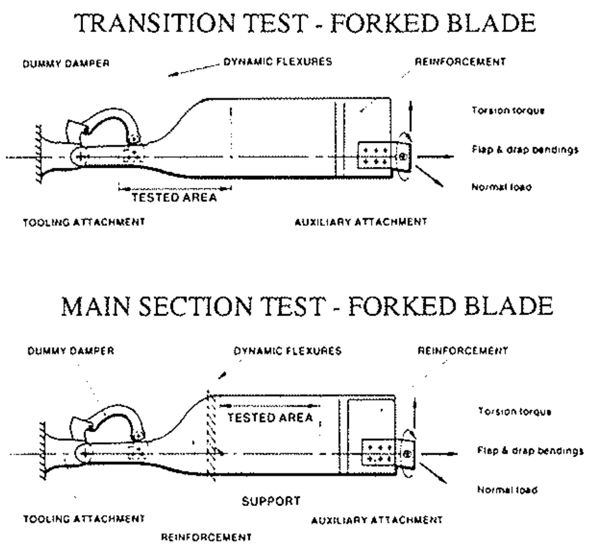



Figure 17. Forked blade tests

The fork transition zone and main blade section were submitted to the same analysis as the attachment zone. The analysis indicated that the exposed portions of the blade had to be qualified for impact damage as well as for lightning strikes and manufacturing defects.

Minimal damage was observed after the lightning test at the AEROSPATIALE research center (Suresnes) facility. Nevertheless, a fatigue test was performed on the blade to allow for the new fork concept and the complexity of the zone in which damage such as internal delamination (undetectable by nondestructive examination methods) could have appreciable consequences. The test demonstrated blade safety with regard to a lightning strike, and substantiated the minimal degree of damage, ensuring blade repairability.

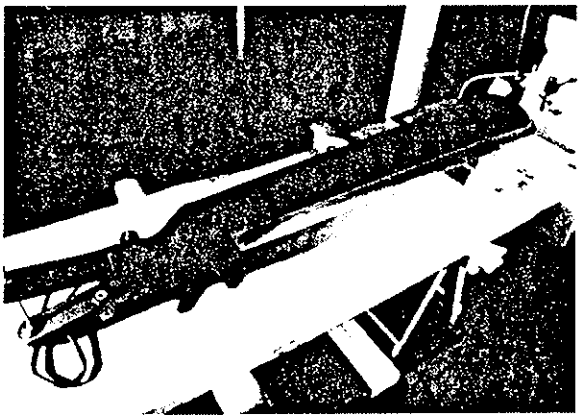


Figure 18. Lightning test set-up

As for the attachment zone, intentional molding defects were produced on a blade section; here again, the test defects were difficult to detect by non-destructive means: missing one carbon ply, reverse lay-up of the two carbon fabric plies forming the rib in the main box. The main blade section and fork areas were not significantly affected by these defects.

Frontal impact damage was investigated using an experimental approach in compliance with the requirements specified by the French authorities. A demonstration had to be provided that, following a frontal impact by a 1.8 kg bird or by a 100 g metal object, the aircraft was capable of continuing flight for at least half an hour and subsequently landing in complete safety.

Three blades were impacted to cover all types of impact conditions and locations. Impacts sustained in rotation showed that blade integrity was maintained with no appreciable effect on stiffness. Additional rotation tests were conducted at speeds 30% above the normal flight speed. The subsequent blade examination results clearly demonstrated the role of the ribs and spars in limiting debonding and incipient delamination. For ice lump strickes, internal previous tests shown that this agression was less severe than metallic solid impacts ; so no particular test was performed.

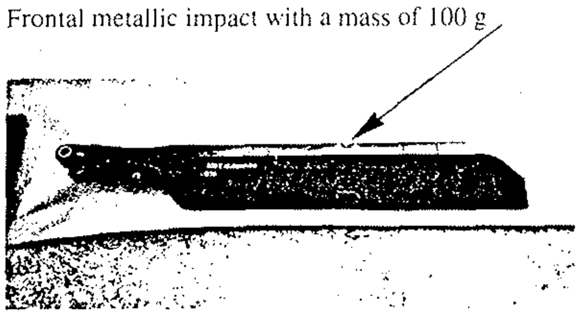



Figure 19. Impact damage test

The blade skin damage tolerance was assessed by proceeding with fatigue tests after initiating cracks in critical blade zones to observe their propagation behavior under dynamic conditions at maximum inflight loads with the multiplier factor of 1.35 as noted above. The demonstration was obtained for two blade sections, largely substantiating the mission completion requirement. The damage showed no propagation (Figure 20) : the structural components (spars and rib) offered multiple paths to sustain the loads.

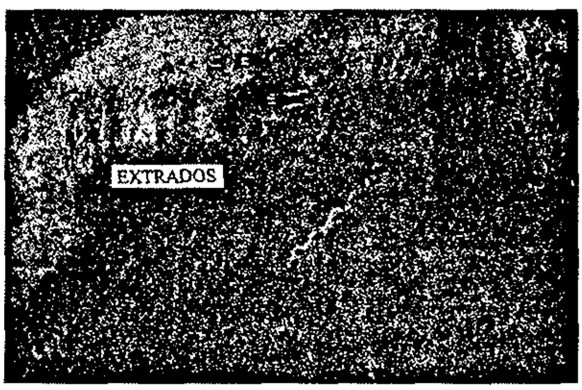
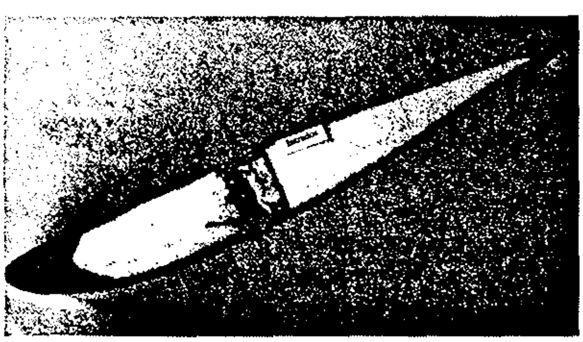



Figure 20.
Crack in main blade section: no propagation

Following the test sequence intended to demonstrate the damage tolerance of the 332 L2 blade design with respect to "civil" aggressions, an additional test was conducted by firing 12.7 mm caliber bullet at the blades. The examination results provided positive data concerning the overall behavior of the spars and ribs: the damage was relatively limited and did not result in airfoil destruction, which would have had catastrophic effects (Figure 21).



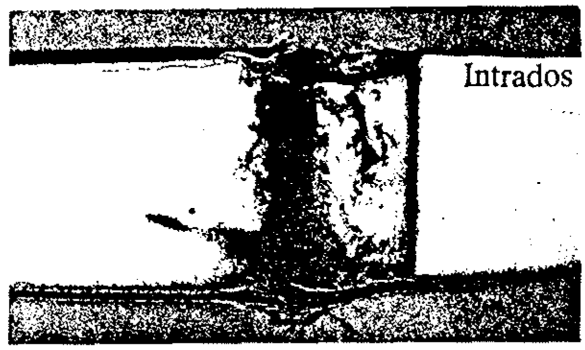



Figure 21. 12.7 mm bullet impact

## 5. CONCLUSION

No claims of exhaustivity are made for the methodology adopted in designing the 332 L2 tail rotor blade. This experience did provide a solid basis for addressing the "damage tolerance" approach now required by civil regulations concerning the fatigue substantiation of helicopter dynamic components.

Some important points were evidenced during this study:

- Determination of the safety factor for substantiating non propagation.
- The need for data on the in-service behavior of similar aircraft parts in order to define the damage limits to be taken into consideration.
- Analysis of molding defects in specifying manufacturing processes.
- Implementation of a defect and criticality analysis procedure from the component design stage.

In the face of new regulatory requirements, helicopter manufacturers will necessarily develop and implement more sophisticated technological concepts that will further enhance safety and reliability, as was the case for the tail rotor blades developed for the AS 332 L2 helicopter.

## REFERENCES


[1] M.G. Clemmons, *Antitorque Safety and the RAH.66 Fantail*, AHS 48th Forum, Washington DC, June 1992.

[2] M.Vialle and G. Arnaud, *A new generation of Fenestron Fan-in-Fin Tail Rotor on EC 135*. ERF 19th Cernobbio Sept. 1993

[3] L.S. Buurma and A. Dekker, *Bird Strike Hazards to Helicopters*, RNLAF, Netherlands.