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NON-DESTRUCTIVE TESTING OF COMPOSITE STRUCTURES

by

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ABSTRACT

The development of composites has revolutionized the aeronautical industry:

Weight saved through the use of composites has made it possible to increase the performance of aircraft. Moreover, the high resistance of these materials to the effects of environment is an important operational safety factor.

The application of composites to helicopter structures is particularly remarkable as composite structures account for 25 % of the DAUPHIN or CHINOOK structural weight.

Composite technology being new, the effect of variations, although slight, of some parameters on structural performance is not yet fully understood.

Therefore, manufacturers must be very strict both in their definition of components and in the application of subsequent transformation and inspection methods.

With composite parts, one obtains the material and the final part simultaneously during the curing process, while metal part processing requires separate operations.

Manufacturing defects may consequently appear not only at junction areas but also at the very core of composites.

The purpose of non-destructive tests is to detect such defects and thus determine the conformity of parts.

Various non-destructive testing methods have been developed for this purpose:

-simple methods like tapping or x-ray inspection or more complex ones like ultrasonic inspection or Laser holography are a commonplace in the production process.
-other methods like acoustic emission, computed axial tomography, thermography or eddy currents are on trial.

This paper describes the general principle of each method as well as some application examples.

It is also evidenced that selection between the various methods proceeds from prior assessment of technical imperatives such as the characteristics of the part to be inspected and the type of defects sought as well as financial considerations as to the cost of these inspection methods, which may prove rather high at times.

1 - INTRODUCTION

The use of composites on helicopters is not new as, for example, the cowlings of the ALOUETTES, as far back as 1950, were already of glass/polyester.

However, not until the 70ies did composites achieve full recognition with the production of the SA 341 Gazelle and Bölkow 105 main rotor blades, then, in 1975, with the Starflex main rotor head of the AS 350 Ecureuil.

These materials are making a tremendous breakthrough nowadays.
In the field of blades, the major American manufacturers are beginning to mass-produce partly or entirely composite blades (Boeing Vertol's CH47 and 234, Sikorsky's S76 and Bell's 214) and their European counterparts are also developing entirely composite blades.

As regards rotor heads, the only mass-produced composite products are Aerospatiale's Starflex main rotor head and Sikorsky's Cross Beam tail rotor hub.

New developments are on their way like Boeing Vertol's Bearingless Main Rotor (BMR) and Aerospatiale's Triflex.

Composites have begun recently to make their way into primary structures, like:
-the floors of the Boeing 234
-the horizontal stabilizer of Sikorsky's S76
-the fins and stabilizers of Bölkow/Kawasaki's BK117.
-the fins and stabilizers of Aerospatiale's AS 365 N Dauphin.

We can estimate the average percentage of composites in a new-generation helicopter empty weight (engines and ancillary systems excluded) at 20 to 25 %.

There is every reason to believe that the present developments in the field of primary structures like Bell and Sikorsky's ACAP (Advanced Composite Airframe Program) supported by the US Army will increase this percentage to 30% in the next five years.

Given the fact that this technology is relatively new, there remain many unknowns as regards the influence of the parameters of the raw materials and of their fabrication methodology on the final performance of the parts.

To remedy the lack of knowledge in this field, thorough checks must be made at the following three levels:

- on raw materials and semi-finished products (we must work on suppliers).
- on the fabrication of parts at the manufacturer's.
- on finished parts.

Non-destructive testing, the very topic of this paper is performed on the last item of the list: finished parts.

2 - FABRICATION METHODOLOGY OF COMPOSITES.

This is fundamentally different from that of metals since the material is wrought at the same time it becomes a finished part.

Moreover, composites are two-phase materials: fiber and matrix.

There are numerous fabrication methodologies for composite finished parts according to the type of semi-finished product available on the market.

-unidirectional tapes and prepregs

these are the most commonly employed materials in the aeronautical industry. Cutting is manual, semi-manual or automated (Laser, water jet, Gerber Cutter) and laying up is most of the time manual. Curing takes place in a mold where the material is submitted to temperature on the one hand and pressure or volume on the other hand.

-unidirectional tapes, fabrics or dry braids impregnated in situ.

an operation is added: impregnation. This can be done either manually by contact or by injection into a closed mold.

-winding of wicks or ribbons that are either pre-impregnated or submitted to in-situ impregnation.

This process is entirely automated which guarantees better reproducibility of the quality of parts.

-compounds or short pre-impregnated fibers.
These are wrought by compression or transfer for the fabrication of large parts.

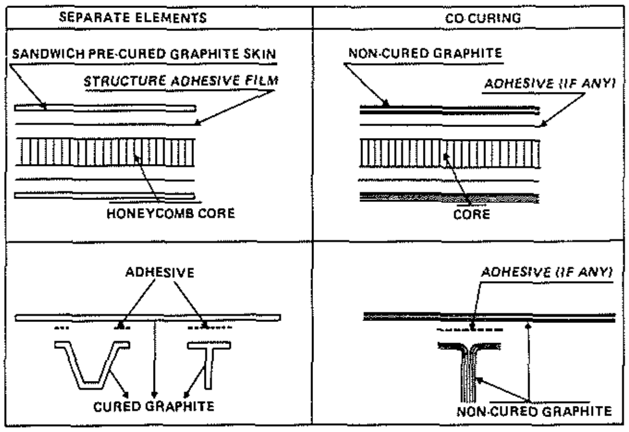


FIG. 1 : COMPOSITE STRUCTURES FABRICATION PROCESSES

Complex parts, be they single-blocked or of sandwich construction, can be fabricated along two fundamental lines:

- co-curing which has the obvious advantage of being a low-cost methodology but does not allow a detailed inspection of internal areas.

- assembling (mechanical or bonding) of pre-cured elements which offers a better guaranty that each constituent is perfectly sound.

The above list shows that, with the exception of a few automated operations, a large number of fabrication phases remain manual and may therefore be the source of defects.

Moreover, variations in the composition of resins or in the curing cycle (pressure, time, temperature) can generate additional defects during curing: separation of layers or cracks due to thermal stresses, porosity, waviness, etc..

3 - STRUCTURE TYPES

Depending on weight, stiffness, strength and vulnerability imperatives, the designer has to choose between two structure types: single-block or sandwich structures.

Single-block structures

Be they stiffened or not, these structures are characterized by a stack of plies whose total thickness can vary from a few tenths of millimeters to a few centimeters. Such is the case :

-for secondary structures like doors, cowlings and various supports
-for primary structures like the horizontal stabilizer, the fin leading edge, blade-tip caps, and certain tubular spars.
-for vital rotor components like the Starflex head, blade spars and horns.

Sandwich structures:

These are particularly prized when both stiffness and minimum weight are necessary. They comprise a Nomex-type honeycomb structure covered with metal or composite skins.
In some cases, a bead of adhesive is added for a better honeycomb-to-skin adhesion.
Many helicopter parts are fabricated in this manner: various cowlings, fins, tail booms, floors, blade trailing edges.

4 - DEFECTS MET AND THEIR EFFECTS.

Structural defects can appear during fabrication or use of composite parts.
Roughly speaking, they can be broken down in the following categories:

4-1.Single-blocked structures.

a/Porosity

This is the most frequent defect. It is mainly due to faulty compaction of the laminate, liberation of volatile products, or insufficient control of the evolution of resin viscosity during cure.
Porosity can be concentrated (penalizing case) or distributed all over the product.

It can be defined by an areal percentage per laminate fold or by a voluminal percentage.

Porosity affects above all the mechanical characteristics of composites where the resin is involved.

Thus one notes 30 to 50 % drops in flexural, shear and compression strength for an areal porosity rate of 10 %.

Moreover, a porous material can absorb more water and become sensitive to icing and internal swelling. Micro-porosity at the fiber/resin interface also favor degradation induced by rapid temperature changes.
The porosity rate that must not be exceeded for production depends on the use of the part and the associated calculation margins. It is generally between 3 and 10 % on aeronautical structures.

b/Delaminations

these are major structural defects as they indicate layer separation. They may appear both during fabrication or in service.
Like porosity, they affect the mechanical characteristics where the resin is involved: interlaminar shear, compression.

The most substantial drops in strength are those observed with interlaminar shear: 30 % for a defect affecting about 5 % of the area concerned.
When they crop up in service, these defects grow if the part is submitted to fatigue strain. However, they do not, in many cases, affect the main functions of the parts nor safety (fail-safe behavior).

c/Misshapes.

these are for example waves or folds made by rovings, tapes or fabrics. They crop up during molding and can be caused by a faulty cut of prepregs or by a wrong law of variation with time of temperature and pressure during curing.

Acceptance or rejection criteria will be essentially based on curvature radii, which affect both the strength and the modules in the direction of reinforcements.
Moreover, one can note also fiber orientation defects whose effects can be foreseen theoretically.

d/Uneven distribution of resin.

resin distribution is on the whole well mastered. Given the scatter generally observed, one can consider that this parameter has less influence than the preceding parameters. Its static and fatigue effects are well known today both theoretically and experimentally.
However, it is worth checking that scatter remains within acceptable limits within a same part.

e/Various inclusions

these can be a separator left behind, chips, etc ...
They must be detected after fabrication.

f/Notches, dents, impacts.

these appear mainly in service (impacts in flight) or during handling. They can lead to a failure of fibers visible at the surface of the part or to internal separations.

The presence of a hole or notch, according to the type of draping, will lead to a 25 to 65 % drop in static tensile strength and will little affect fatigue strength.

A 4 joule blow on a 3-millimeter thick skin generates damage invisible to the naked eye but reduces the tensile strength of the composite by 20 % and its compressive strength by 35 %.

4-2.Sandwich structures.

The same defects found in single-block structures can also be found in the skins of a sandwich structure.
In addition, some defects are specific to sandwich structures:

- -lack of adhesion between skin and honeycomb.
- -buckling or flattening of honeycomb
- -"telegraphing" (honeycomb visible through the skin)

While telegraphing seems to be more a surface condition problem than a real strength problem, the other two problems have an immediate effect on flexural and shear strength.
These defects are not admissible and must therefore be detected.

4-3. Bonded structures

Two types of defects can be observed.

-faulty thickness of bonding area

Calibrated-thickness adhesive films are most commonly used for structural bonding. However faulty application of the film can lead to uneven thickness and hence to a change in shear strength. The strength can drop by 25 % when the thickness increases from 0.1 to 0.3 mm.

-local lack of bonding

In the absence of particular overstress at edges or too significant separations, the loss in shear strength is pretty much proportional to the separation area.

Generally speaking, aging effects do not add up directly to those mentioned above and rather affect the resin (porosity, lack of cohesion): the effect of aging makes itself felt less on a material with defects than on a sound material.

5 - PURPOSE OF NON-DESTRUCTIVE INSPECTION

As indicated previously, structural defects do not affect performance in the same manner. Therefore they must be controlled if we want to guarantee constant compliance in the long run with what had been defined and accepted initially.

We see to it right from definition and industrialization that we opt for the most reproducible materials and processes and that this choice contributes towards mastering the soundness of the parts.

However these precautions do not always suffice to guarantee entirely the quality of the finished parts. Therefore additional checks must be performed to determine the compliance of parts with maximum admissible defect criteria established theoretically or experimentally according to their effects on performance and to the safety margin desired: such is the purpose of non-destructive testing.

Beside this part quality assurance aspect, the results of non-destructive inspection are processed with a view to identifying a possible deterioration of quality with time that would be attributable to the materials or processes and would be likely to become inadmissible in the long run. The follow-up of quality thus achieved is one of the indicators on the "industrial instrument panel" that makes it possible to ward off possible industrial risks.

6 - EXAMPLES OF NON-DESTRUCTIVE INSPECTION METHODS.

Aerospatiale's Helicopter Division categorizes them according to their degree of utilization.

6-1 METHODS APPLIED IN PRODUCTION.

Sonic inspection.

This method consists in tapping lightly the surface of the skin with a rigid body that must be less hard than the skin. The difference in sound between the bonded area and the non-bonded area is noticeable to the ear.

FIG. 2 : SONIC INSPECTION ON A HELICOPTER BLADE

It requires however a certain experience in the interpretation of sound differences.

When applied to sandwich structures like main or tail rotor blades, this method makes it possible to evidence defects like a separation of film-to-honeycomb or skin-to-film joints.

Mechanization of this process can be envisaged.

Ultra-sound inspection

General principle.

This inspection consists in evidencing the heterogeneity of a structure or of a material through the transmission of an ultra-sonic wave into the part and the comparison of the signal received to a master signal.

Sonic resonance method.

This uses low-frequency ultra-sounds (150 to 300 khz) and consists in exciting the part with a probe and in comparing the resulting mechanical vibrations (amplitude, phase or frequency) to those obtained with reference parts.

The structure is excited through direct mechanical contact with the probe

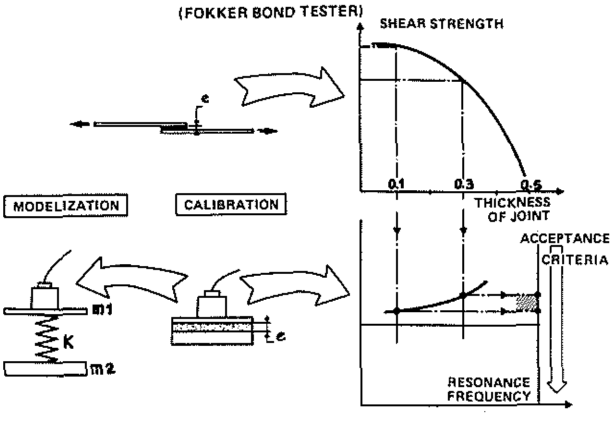


FIG. 3 : ULTRASOUNDS : SONIC RESONANCE METHOD

Among the available instruments, we can mention the FOKKER BOND TESTER used for inspecting bonded metallic structures and the BONDASCOPE for bonded composite structures.

The probe of the Fokker Bond Tester is constituted of a piezoelectric ceramics. The excitation frequency is scanned in a small adjustable band of the frequency range. The band is selected according to the nature of the structure that must be inspected. The resulting mechanical vibration is detected and its frequency is analyzed for metal/metal bonded assemblies. In that case, acceptance criteria affect the thickness of the bonding joints.

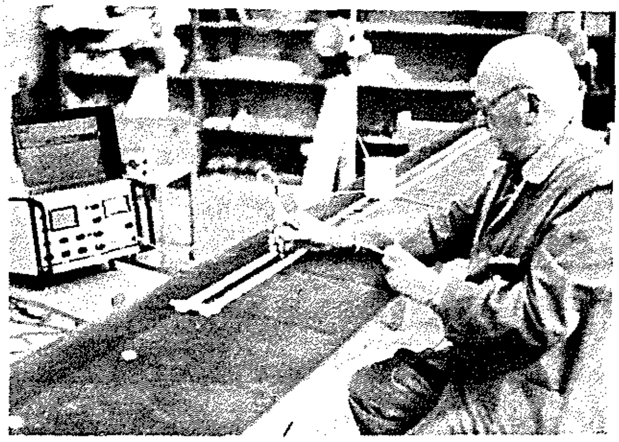


FIG. 4 : BLADE BONDING INSPECTION WITH FOKKER BOND TESTER

The probe of the Bondascope, too, is a piezoelectric ceramics excited at a fixed frequency. The phase and amplitude of the resulting mechanical excitation are analyzed for checking composite/composite bonded assemblies. In this manner, any lack of bonding can be evidenced.

These two instruments require - for the various levels of structure quality - calibration diagrams indicating the sonic resonance characteristics of the probe-structure assembly.

They are used intensively for checking the bonded structures of the SA 365 N Dauphin.

Transmission method

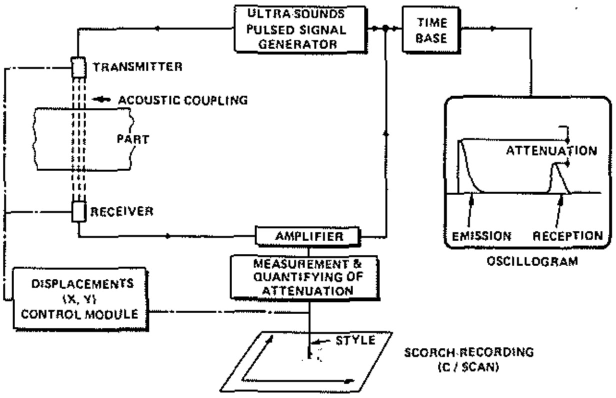


FIG. 5 : ULTRASOUNDS : METHOD BY TRANSMISSION WITH C-SCAN RECORDING

This consists in measuring the attenuation of an ultra-sound wave due to its crossing the structure or the material between the transmitter and the receiver. The transmitter and the receiver may be separated or not separated and placed on either side or on the same side of the structure subjected to inspection (simple or double transmission path according to the material and the thickness of the structure).
This method utilizes high-frequency ultra-sounds (1 to 40 MHz).

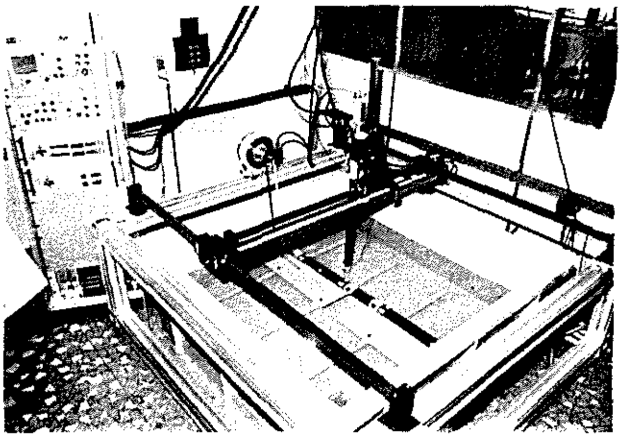


FIG. 6 : TRANSMISSION ULTRASONIC INSPECTION INSTALLATION

The attenuation of the ultra-sound signal amplitude can be expressed on paper through plateaus of various heights recorded thanks to the scorch technique. The fact that the motion of the sensor on the part is coupled with that of the style makes it possible to record an ultra-sound image of the part which evidences internal structure defects (heterogeneity, separation, porosity). This recording method is called C/scan. It is mainly used for inspecting single-block glass or graphite composite parts like the Starflex star (fabrication follow-up) and single-block graphite tubes or ribs of the SA 365 N Dauphin fin.

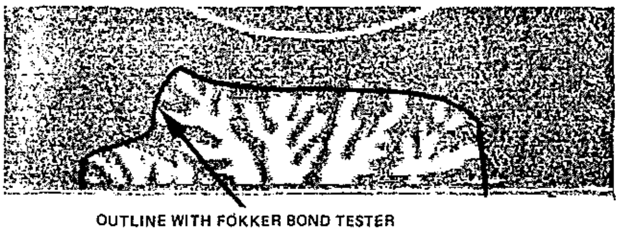


FIG. 7 : COMPARISON BETWEEN RESULTS OF C-SCAN AND FOKKER BOND TESTER ON A METAL/METAL BONDED ASSEMBLY

X-ray inspection

The use of X-rays is not new and while technological progress has been achieved, the process remains very conventional.

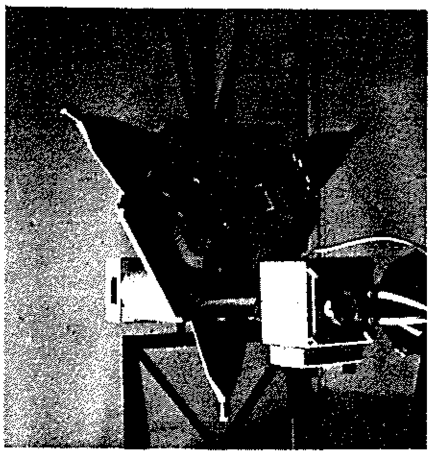


FIG. 8 : X - RAY INSPECTION OF A PART

As a reminder, we shall mention the various techniques used:

-radiography or production of a picture on a photographic film. It gives best resolution.

-radioscopy or excitation of a fluorescent screen which is associated with a light intensification device and allows to obtain an image on a cathode ray tube.
This method is faster, interpretation of the image can be immediate. However, resolution is lower than that obtained with radiography.
These two methods are applied on the Starflex head (star and blade attach bars).

-radioxerography or the impression of a semi-conductor layer (electrostatic process).
This method offers greater tolerance for x-ray absorption density variations of materials. It allows a good visualization of isodensity range contours.
It can, in some cases, compete with radiography as, while it is less accurate, it is much more economical.

This method which is being evaluated presently proves to be applicable on parts like small blades or graphite single-block parts (blade horn).

Holographic interferometry.

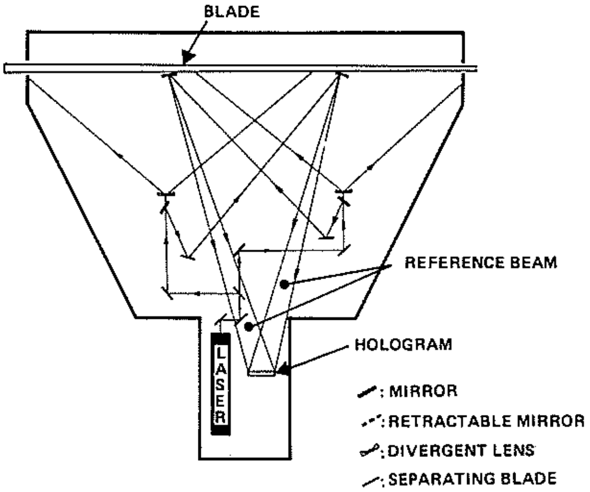


FIG. 9 : HOLOGRAPHIC INTERFEROMETRY INSPECTION OF COMPOSITE BLADES

This is an optical method which allows to evidence through interference fringes micro-distortions at the surface of the structure under inspection. These micro-distortions are due to internal defects which perturb the deformation of the structure under mechanical or thermal stress.

The result is obtained by the interference of a holographic image with the image of the deformed object or that of two images of the same object before and after deformation.

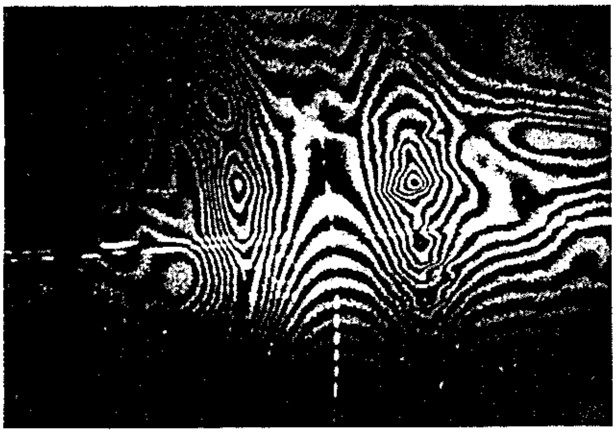


FIG. 10 : EXAMPLE OF INTERFEROGRAMS

Black interference fringes appearing at the surface of the object indicate a deformation difference of $\lambda /2$. One can thus obtain a network of iso-deformation lines.

There are two techniques in this field:

-double exposure technique where two waves transmitted by an object at two different stages of deformation are stored on the same hologram (double exposure). An interferogram appears then on the photographic plate. This is the simplest and easiest technique. The problem is that this technique is limited to comparing only two deformation stages.

-real time technique where the original wave of the object stored on the plate interferes with the waves of the object at various deformation stages. This technique demands a most rigorous setting of the photographic plate after processing. This is more difficult to implement but this has the advantage of allowing dynamic (real time) observation of the phenomenon.

The mechanical deformation of the structure can be obtained in various ways:
-through impacts
-through vibrations
-through differences of pressure (positive or negative).
-through heating

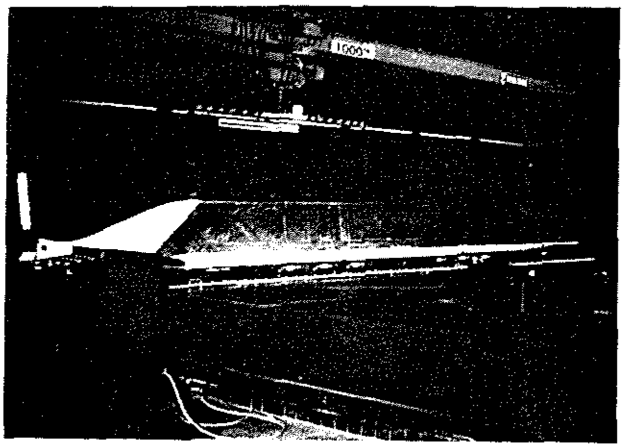


FIG. 11 : HOLOGRAPHIC INSPECTION INSTALLATION FOR BLADES

This method is applied to production inspection of SA 330 Puma, AS 332 Super Puma and SA 365/366 Dauphin main blades.

Blade deformation is obtained through external pressure reduction. This method is very effective for evidencing bonding defects in honeycomb/skin and foam/skin assemblies and delaminations in skins made of glass and graphite.

Stiffness measurement

This method considered global makes it possible to verify the major mechanical characteristics of a part.
Both the load applied and the deformation are measured.
It is used in production for checking the arms of the Starflex star.

It is sensitive enough to evidence the absence of one out of the 25 layers constituting the arm.

Mechanical proof testing.

This is a global inspection method which makes it possible to examine the entire part. Loads are applied and the behavior of the part - its deformation and acoustic emission (see para 6.2) - is recorded at the same time.

It is generally used for detecting a structural anomaly in the part. Then the part must be submitted to a more detailed examination with a view to identifying the anomaly.
This method is presently being used on the support tube of the SA 365 new Fenestron tail rotor and on the new composite fin.

6-2 METHODS ON TRIAL.

Acoustic emission

General principle
A material subjected to loads, damage or structural modification releases energy in a discontinuous way and generates waves which propagate at the surface of and within the material.

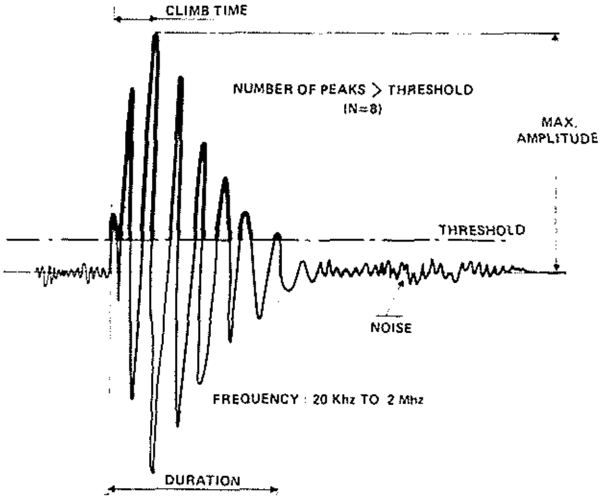


FIG. 12 : ACOUSTIC EMISSION

This wave is picked up by a piezoelectric sensor and is then transformed into an electric signal in the shape of a damped sinusoid.
The signal which represents an event can be identified by:

N:number of peaks beyond a given threshold
T:duration of event
A:maximum amplitude

These various parameters, recorded as a function of time and of a mechanical parameter (load, pressure,...) can be processed either statistically (cumulation, rate,...) or with distribution functions. They must make it possible to characterize damage (if any) within a structure under stress.

It is possible to locate the damage through a triangulation process using several sensors.

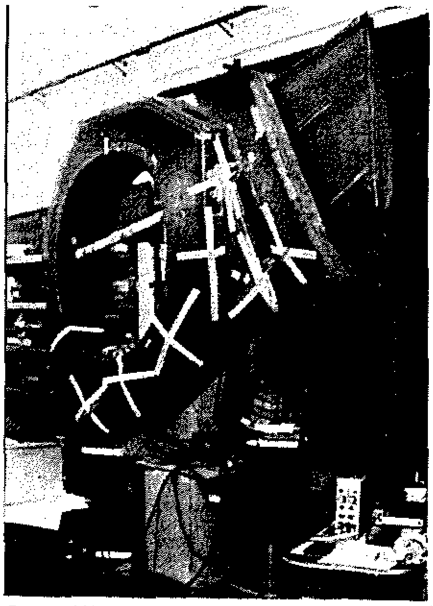


FIG. 13 : DAUPHIN DERIVATIVE ON ACOUSTIC EMISSION TRIAL

Practical examples.
This method is applied for proof testing a graphite/epoxy and kevlar/epoxy composite fin/Fenestron assembly.
Eight sensors are placed on the structure.

A step loading procedure is applied and at the end of each step, the load is reduced by 200 daN.
A certain number of significant curves can be lofted on the basis of data gained during tests:

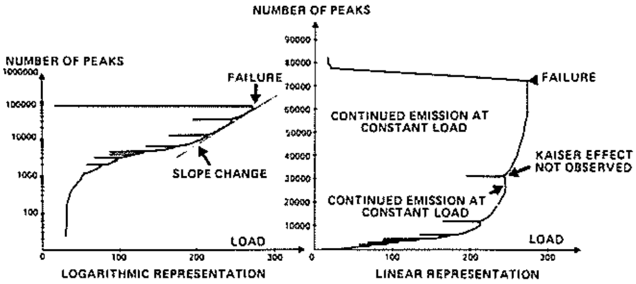


FIG. 14 : ACOUSTIC EMISSION : SIGNAL PROCESSING

a/ the acoustic emission curve being exponential one can loft
log N (number of peaks) = f (load) which is linear.
A change in the slope is observed at 70 % of failure load

b/ curve : N (number of peaks) = f (load).
It presents two interesting characteristics namely, observance or non-observance of Kaiser effect (emission during a second identical loading) and continued emission at constant load (noticed beyond 70 % of failure load).

c/ accurate location of emission area and comparison of levels of emission from various sensors.

d/ amplitude distribution curve as loading progresses.

Conclusions.

This type of check should make it possible to make sure that the load applied during proof testing does not damage the element being tested and that proof testing is run at a load at the most equal to x % of the failure load (x being determined previously through tests).

Loading and listening criteria must necessarily be defined on the basis of the type of structure or element to be tested.

Computed axial tomography

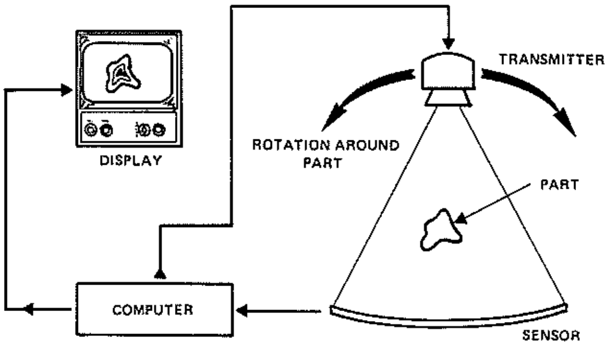


FIG. 15 : COMPUTED AXIAL TOMOGRAPHY (CAT) PRINCIPLE

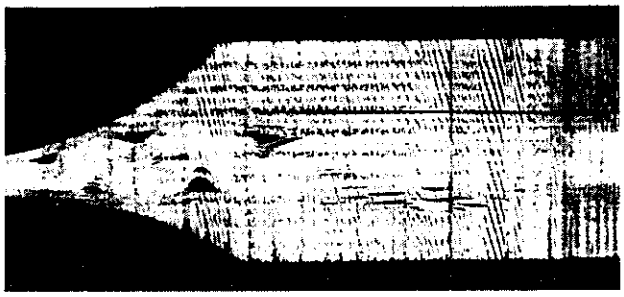
General principle.

This is an x-ray scanning technique involving a computer.
A plane x-ray beam crosses the part under examination and hits a series of detectors. The transmitter/detector assembly rotates 360 ° around the part. Then the results are processed by the computer in order to reconstruct the densitometric image of the cross-section.

Work performed.

The only way we could test the possibilities of this technique was by resorting to medical CAT scanners, the only equipment available today. To that end we "auscultated" a certain number of mechanical parts and more especially a glass/epoxy composite arm of a Starflex rotor head in which we had generated defects.

CAT IMAGE



MECHANICALLY CUT
ACTUAL PART

FIG. 16 : CAT ON STARFLEX HEAD

Figure 16 shows the mechanically cut section of the actual part and the densitometric image of this section before cutting.

Another example consisted in verifying the correct distribution of 3 mm diameter fibers in an arm made of silicone elastomer.

Advantages and disadvantages:
The great advantage of this equipment is its ability to reach and isolate a small volume within the structure.

The CAT equipment available today is expensive and ill adapted to industry requirements.
This type of inspection would be viable from an industrial standpoint if greater power (on the order of 400 kv instead of the present 130 kv) and simpler equipment with a certain adaptability potential (e.g. kits) were available.

Infrared thermography

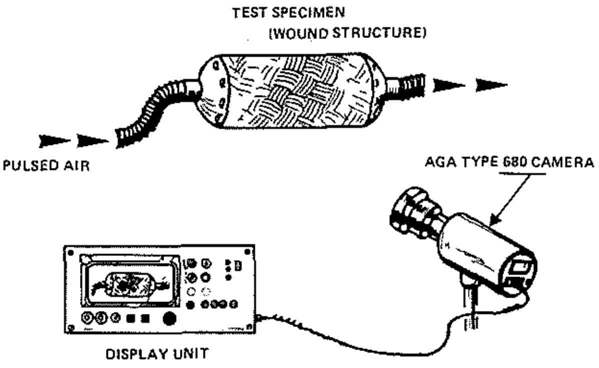


FIG. 17 : INFRARED THERMOGRAPHY INSTALLATION

Inspection of wound structures

This method has been used on an industrial scale by Aerospatiale since 1970 for inspecting wound cylindrical structures of space launchers.
It makes it possible to detect two types of defects within a very short time:

- delaminations between composite layers.
- separations in metal/composite and rubber/composite assemblies at the bottom and on the walls of the structure.

The heat flow between the two sides of the wall is altered by the existence of these defects which generates a thermal gradient (independent of the defect thickness) noticeable with a thermographic camera.

While it rotates about its rotation axis at a rate of 1 rotation per minute, the structure is heated from the interior either by warm air or by an infrared light ramp located parallel with the cylinder generators.

The image obtained on a CRT evidences the thermal gradients in the structure as colored isotherms are displayed.

This method allows to detect 2 cm by 2 cm defects and is applied successfully to wound glass or kevlar structures. For high thermal conductivity materials like graphite, it cannot be applied directly since the duration of thermal gradients does not exceed a few tenths of a second. It is therefore necessary to resort to magnetic recording and subsequent numerical processing.
This process as well as stroboscopic inspection (see below) are employed at the Helicopter Division for monitoring part testing (especially fatigue testing).

Stroboscopic inspection

The thermal image obtained with this technique - maximal amplitude and minimal amplitude - makes it possible to locate maximum dynamic deformation areas corresponding to maximum thermal gaps.

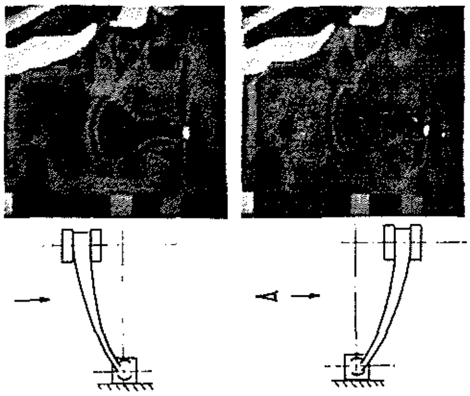


FIG. 18 : LOCATION OF OVERSTRESS AREAS IN A STARFLEX HEAD THROUGH INFRARED THERMOGRAPHY

7 - CONCLUSION.

Thanks to their wide experience in operating the various non-destructive inspection methods, inspectors have available today a wide range of means for detecting macroscopic defects.

With a view to better adapting these methods to aeronautical applications and to calibrating them entirely for a better image-observed-to-real-defect correlation, some optimization work is necessary.

It will also be necessary to expand the use of global detection methods (IR thermography, holographic inspection) which make it possible to display an entire part in one single operation, anomaly identification being performed, if necessary, via a local method.

However, non-destructive testing is not an end in itself and it can affect the cost price of a part by up to 10%

	TOTAL INSPECTION COST FABRICATION COST	NO INSPECTION COST FABRICATION COST
STARFLEX STAR	35 %	10 %
STARFLEX BLADE-ATTACH BARS	20 %	4 %
MAIN PUMA BLADE	15 %	2 %
DAUPHIN TAIL CONE	20 %	10 %

Therefore it is necessary to reduce the cost by short and medium-term actions:

In the short term non-destructive testing, cost can be cut by appropriate automation of processes and adaptation of the means implemented to acceptance criteria.

In the medium term, one can hope that the effect of defects on structure performance will be better known and consequently that acceptance criteria will be expanded.

Finally, non-destructive testing work could be reduced through a constant quality improvement effort at all levels:

- at the raw material producers' who could guarantee improved reproducibility of their basic products through better cooperation with aircraft manufacturers.
- at design level; design will have to be as simple as possible to avoid fabrication methodology acrobatics.
- finally at fabrication level by adopting methodologies allowing better control of the quality level desired.