Actual Processes and Researches at Eurocopter on Failure Investigation of Metallic and Composite Parts

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ABSTRACT

Eurocopter's approach on parts Failure Analysis is presented for both Metallic and Composites. Actual processes: For Metallics, nature of the failure (Fatigue/Static Progressive/Brutal) is determined from part deformation, grain flow & fracture surfaces (macro/micro scale, SEM/TEM). Compared with stress calculations (direct or reverse), it enables to confirm scenario of ruin. For Composites, same methods are less convincing and it's often difficult to determine type of rupture: Broken parts have only little (or no) deformation; Ruin process is diffuse; Failure often crushes fracture surfaces. Researches are conducted to reduce cost & time on failure analysis process. For Metallics they concern: da/dN measurement by topography; beach mark interpretation; SIF calculation of 3D cracks with contact. For Composites, recent progresses allow to estimate: Damage zones & levels; Failure initiation loads. Combining prediction with 3D observation, and thanks to high resolutions reached from small size sources, new investigation methodology for composite parts can be envisioned.

1- Introduction

Paper is divided into 4 parts: Helicopter (HC) Product Background, Actual Processes for Failure Investigation, Limitations of Actual processes, Research axis. Obvious material nonconformities are out of the scope of this paper.

2 - Helicopter Product Background

HC parts studied concerns the vehicle. They are divided into 2 main families : Airframe (A) and Dynamic System (DS). DS represents Blades, Rotor Hubs : Main(MRH) + Rear(RRH), and Transmissions : Main Gear Box (MGB), Transmission Shaft, Intermediate Gear Box (IGB) and Rear Gear Box (RGB).

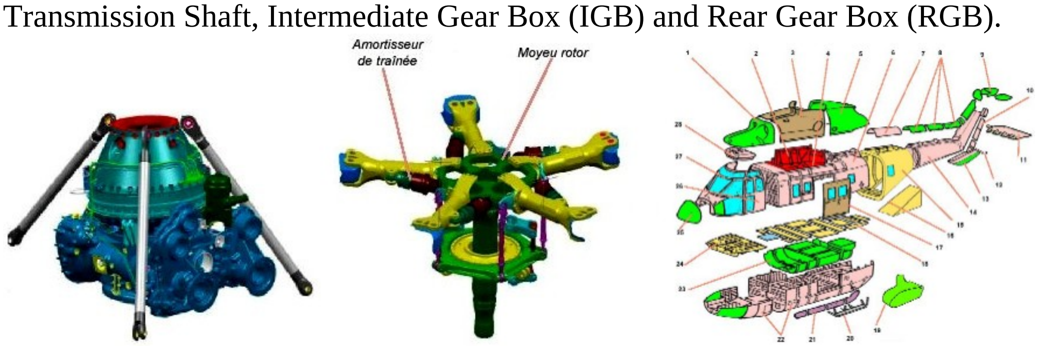

Figure 1 - someHC parts. From left to right : MGB, MRH, Airframe

Materials

MGB are Metallic. For Rotor, Transmission, Rear Blades and Airframe, parts could be Metallic or Composite (organic matrix). Main Blades are Composite. Usage of Composite tends to increase.

Stresses - Dynamic System / Airframe

Stresses on DS Parts are defined by : High vibratory level, R variable in a wide range : $-1 < R < 0.9$, and High Fatigue Spectrum (typically 350*60*4 = 0.1 Mcycles/hour). Under these conditions, DS Parts are sized by Fatigue loadings. Certification calculations are made essentially on crack initiation (Safe Life + Damage Tolerance). Crack propagation is reserved for Airworthiness problems (Inspection Interval). This represents a strong difference between Helicopter & Planes. Stresses on Airframe Parts are defined by : High Static Loadings, Relatively low levels in high cycle Fatigue, Fatigue in Low Cycle. Under these conditions, Airframe Parts are sized by static loadings.

Industrial need : Fast & Efficient Protective Measures

Out of standard priority test results (Static+Fatigue), when an incident occurs during HC usage, Failure Analysis is the key part of "Continuing Airworthiness Process". This process can be divided into 4 steps : Information Gathering And Internal Distribution, Incident Analysis, Protective Measures, Corrective Measures. First Priority is "Protective Measures". It is the center of this paper. Objective is to determine the real propagation time of the cracked part in order to add a well adapted Inspection Interval (II) on the HC fleet. Difficulty is to maintain safety (mandatory) but also (as far as possible) HC usage for customers. It's a a tricky task because simple very conservatives approaches are generally not possible and answer must be rapid.

3 - Actual Processes for Failure Investigation

3.1 Metallic Materials

Process is separated into 2 complementary steps : Fractographic Analysis (FA), Fracture Mechanics Calculation (FMC). Depending on the crack case (data known, data unknown, quality of the Fracture Surface, Topology Complexity) we use FA or FMC or both. On general case FA determines propagation time observed on the cracked part, and FMC gives by reverse approach, the stress level applied on the cracked part. These two major informations allow us to fix II for Continuing Airworthiness.

3.1.1 Typical crack cases

Crack cases are typically 3D in thick parts, with contact effects. Fig. 2&3 present two examples. On Example 1 (fig. 2), we can notice : Relatively Easy visible Beach Marking, Some Beach Marks (BM) are oxydated (not all), Visible slowing down of crack propagation at the end. On Example 2 (fig. 3), we can notice, on A: Beginning of propagation. Clean Flat surface loaded in bending , on B: Transition zone with very complex mixed modes, on C: Return to clean surface (mode I). Quasi constant da/dN values are measured along all the crack path. This indicates a strong load redistribution vs Crack Length (a). This demonstrates very damage tolerant design for this part (multiple load paths).

Figure 2 - Metallic Crack Example 1 : SuperPuma MRH damper fitting (Steel)

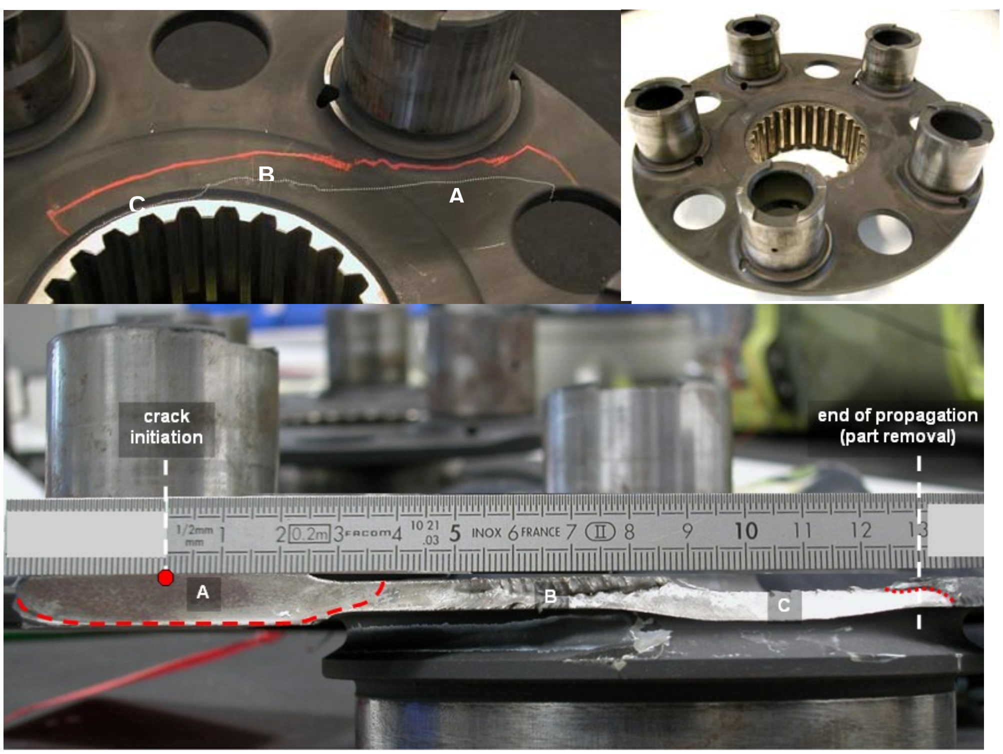

Figure 3 - Metallic Crack Example 2 : Dolphin MGB Planet Carrier (Steel)

<u>3.1.2 Fractographic Analysis</u>

Nature of the failure (Fatigue/Static Progressive/Brutal) is determined from part deformation, grain flow & fracture surfaces. FA is divided into 2 methods : Macro Analysis, Micro Analysis.

Macro Analysis is made on optical microscope under tangential light. This is done by qualified operators. Main result is observation of "Beach Marks" (BM). First results are nature of BM : is there BM visible ? easy visible ? how many families? (principal most visible BM1, secondary BM2, BM3, ...). If it is judged necessary, Second Results is counting of these BM along the crack path. This process is conducted in parallel by several operators. Then, by using engineering judgment, BM can be linked to main change on stress spectrum (e.g. Engine Start, Takeoff,...). Finally, crossing BM counting with Flights Report records, we obtain Crack Propagation Time.

Micro Analysis is made on Electronic Microscope (SEM or TEM). Measurement of Fatigue Striation (when possible) gives da/dN values. Several local measures give then evolution of da/dN vs a. Using this curve, load frequency, and engineering judgment, it is finally possible to obtain an estimation of Crack Propagation Time.

When possible, crossing Macro and Micro results allow increase results quality.

3.1.3 Fracture Mechanics Calculation

Calculations are made using EC internal software PROPAK [3]. This software is based on NASGRO module [1] of ESACRACK 89. Several enhancement [2] have been made "step by step", to fullfil EC industrial needs on real cases. PROPAK main enhancement is "ktl option" added in NASGRO module, which allows for all models, to apply a local correction factor on stress level (ktl) depending on crack length. Curves ktl vs (a,c) are input of calculation. Ktl option can be used to modelize classical Kt effect due to geometry (radius) but also Load redistribution observed during some real crack propagation (as presented by fig. 2 & 3). PROPAK contain also a pre-post processor program who simplify data treatment. For complex geometries, FEM is used to determine stresses to input in equivalent simple models.

3.2 Composite Materials

Actual Composite investigations use methods originally developed for Metallic. Many works were devoted to their application to Composites, however results are less convincing and it is often difficult to determine the type of rupture. Process begins with macroscopic visual and NDT observations. It is generally complemented with SEM fractographic observations. At this scale a statistical analysis is required, and it takes a long time. Fractographic features unique to fatigue failure (striations within the fibre imprints and matrix rollers) are difficult to observe and require high magnification.

4 - Limitations of Actual processes

4.1 Metallic Materials

Fractographic Analysis - Macro : BM interpretation is sometime difficult for specific cases. Some improvement, could be done to refine knowledge on correspondance between BM type and Flying phases. Fractographic Analysis - Micro : da/dN measurement by TEM is not possible on all the range : For da/dN values less than approximately 2 to 5 10-5 mm/cycle (da/dN measur. limit, DML), no measure is possible even if Fatigue propagation phenomenon is still working. Fracture Mechanics Calculation : For very complex cases, pure numerical methods could be usefull to obtain dK vs a curves. Specially in 3D with multiple contacts. And finally, about FM Calculation : it is difficult, and more time consuming, to solve problems on complex geometries with contact using actual process (analytical limit).

4.2 - Composite Materials

4.2.1 Composites specific behavior

Unlike metals, the ruin process of composites, especially in the case of woven reinforcements such as those used by Eurocopter, does not spread from the point where it started, but rather is a diffuse damage phenomenon concerning a volume (figure 4). This is due to the heterogeneous nature of composites and is accentuated by crack blocking, due to fibers crossing in the case of woven fabrics. Thus, relatively short cracks appear in the resin, or at the fiber-resin interface. They remain broadly parallel to fibers, and do not spread at the interface between the plies of the laminate. This is due to the irregularity of this interface for woven fabrics.

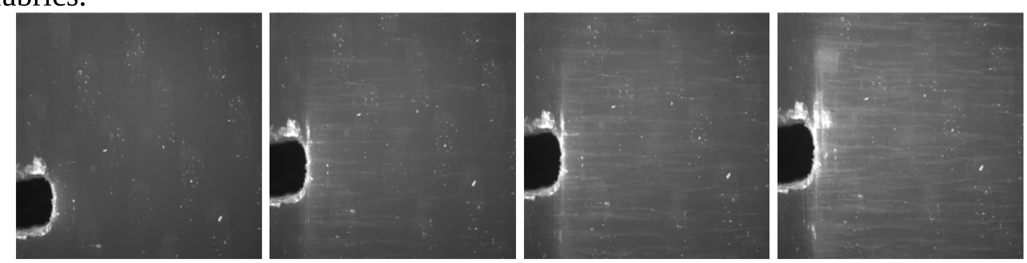

Figure 4 – Volume propagation of damage
Notched plate tensile test on helicopter blade woven glass laminate
(courtesy Laboratoire de Mécanique et d'Acoustique, CNRS– Marseille, France)

Yet unlike metallic materials, fracture occurs in many cases under a load that is not traction, but often compression or shear, or a combination of these situations. The result is a fracture surface having suffered friction and unrepresentative of the loading leading to the rupture (figure 5).

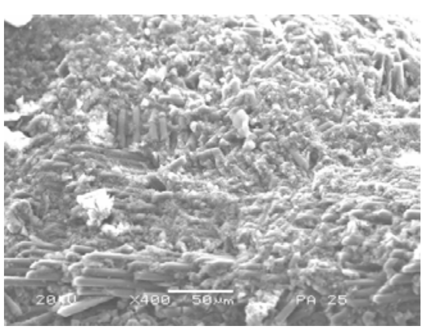

Figure 5 – Crushed fracture surface of a woven carbon laminate under combined shear and compression loading

Finally, and still unlike metallic materials, composite broken parts do present little or no permanent deformation, whose analysis would reduce the difficulties of observation of the fracture surface. This is due to the presence of fibers that are oriented in the direction of the main efforts. After these three statements it is easy to understand why the use of conventional tools, such as observations of fracture surfaces (fractography) and permanent deformations, does not provides as much information for composite parts as for metal parts. Moreover these difficulties are unfortunately magnified for fatigue loading.

5 - Research axis

5.1 Metallic Materials

5.1.1 Fractographic Analysis

FA research works are based on experiments realised at EADS-IW-F [4]. For Macro Analysis, Step 1 is to realise crack propagation tests with specicied load spectrum, Step 2 is to verify if there are some BM visible, as depicted by fig. 6.

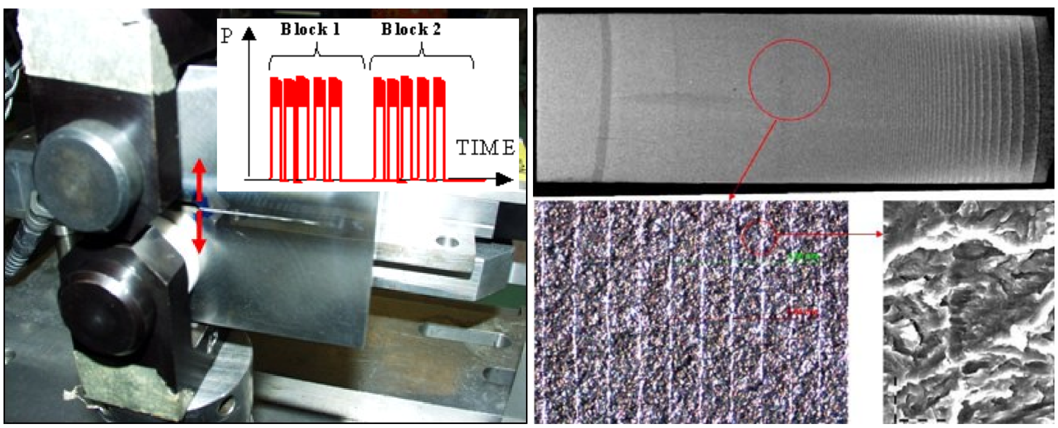

Figure 6 - BM study : From monitored testing to BM signature (Steel [4])

For Micro Analysis, Step 1 is to realise "Reference Specimens" (RS) by propagation tests with monitored da values under different spectrum condition (fig. 7). Step 2 is evaluation of new methods of analyse on RS. One technique is Optical Topology Measurement (OTM). This technique enables to realise the measure without touching the fracture surface. From OTM measure it is possible to determine Roughness Indicators (RI). First results presented from [4] by fig. 8, show potential interest of OTM-RI, which seems to strongly enhance the DML compared to classical TEM capabilities (see §4.1).

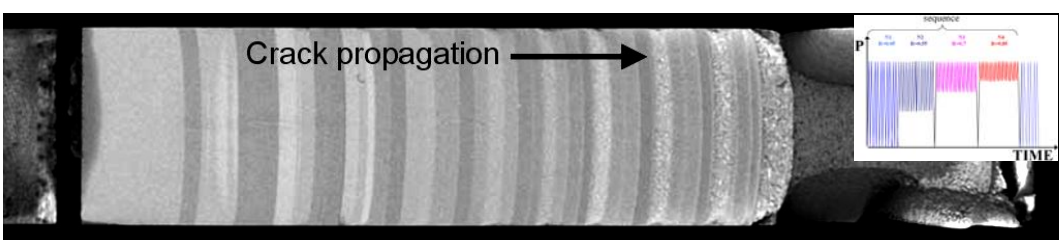

Figure 7 - Ref. Specimen : Various da/dN & R ratio, For each da step (≈ 1 mm) load spectrum is constant. Observation under tangential light (Steel [4])

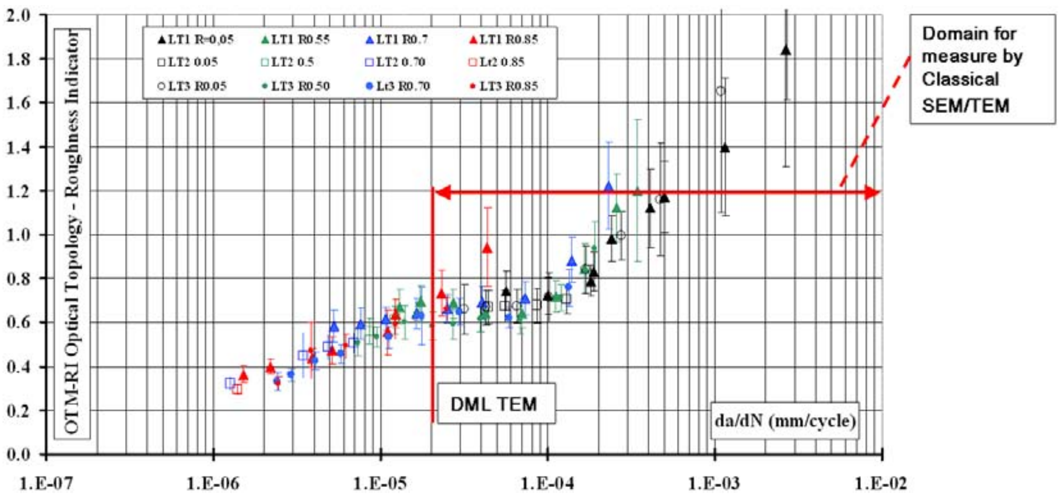

Figure 8 - OTM-RI vs da/dN [4] showing potential gain about da/dN measure limit DML of classical TEM (Steel [4]).

<u>5.1.2 Fracture Mechanics Calculation</u>

To obtain K vs (a,c) curve for 3D complex cases, classical FEM approach is not industrialy efficient for EC needs (too heavy models, time treatment too long). In order to enhance this situation, two axis are studied : FEM+BEM, and XFEM.
FEM+BEM is a cooperation with Ecole Polytechnique, driven by EADS-IW-F L.Chambon [6]. FEM+BEM principle is to blend both approaches in order to keep the best of them. BEM is used in the vicinity of crack (easy mesh management), and Classical FEM is used outside crack area (good for complex limit conditions). The Link between FEM and BEM is obtain by a specific pre-post software, which condense the BEM crack area into an equivalent standard FEM Super-Element.

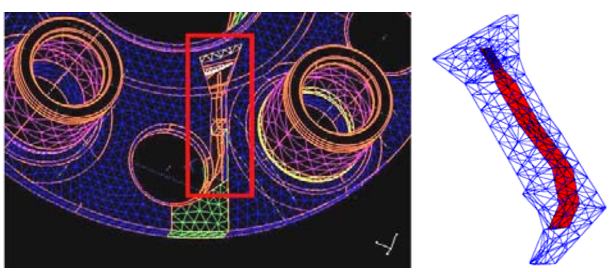

Figure 9 - FEM+BEM on EC case fig.3. Left red rectang.: Super Elem. area in FE Mesh. Right: Crack Surface (courtesy EADS-IW Laurent Chambon)

XFEM approach is begining at EC. EDF-Clamart's open code ASTER [7] or code SAMCEF [8] could be used. Main Interest of XFEM is that crack geometry can be non coincident with FE Mesh (easy to modify). Also, K convergence is good while CPU could be acceptable for industrial use [8].

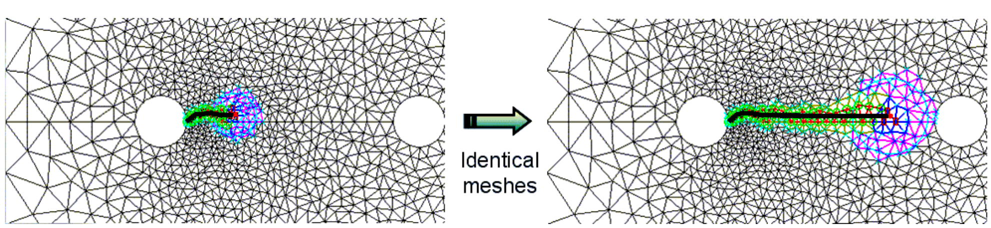

Figure 10 - XFEM example with SAMCEF (Courtesy Bruyneel & Balzano 2005)

5.2 Composite Materials

5.2.1 Exploring the very heart of composites

To go further, expertise methods used successfully for metal parts must be supplemented with special attention at the phenomena of volume damages. With a low density from a radiological point of view, composites have the advantage of being able to be studied by small X ray sources. For this reason they are very good candidates for observation of volumes by micro tomography with a high resolution. Based on density measurements and recently refraction measurements, the volume reconstructions from micro tomography offer many opportunities to analyze the cracks in the damaged plies. But for cracks with a small opening, as in a part after failure, using a high magnification is required, which unfortunately limits the scope of observed samples to few millimeters (figure11).

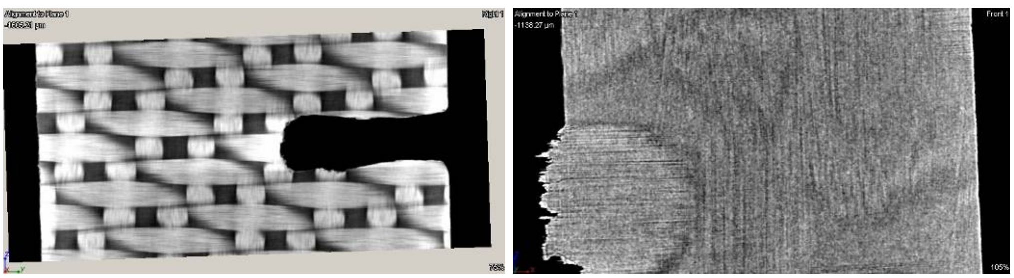

Figure 11 – Reconstruction from micro tomography analysis- left glass sample, right carbon sample(courtesy EADS IW – Munich, Germany)

5.2.2 Virtual testing

Predicting damage and ruin of composites laminated structures is a challenging and complex problem. It involves several mechanisms for the evolution of damage (EOD) operating on various scales from the micro constituents scale, up to the ply scale and then to the laminate scale. A complete set of damage laws has been established for woven carbon and glass plies [9] under monotonous loading. Work is in progress for cyclic fatigue loading [10].These damage mechanisms are generally studied under homogeneous stress states. So to take into account stress concentration at the part scale level we only rely on finite element analysis (FEA). This implicitly assumes that the material behavior is not modified by stress concentration. Unfortunately comparisons between FEA predictions (including EOD) and experiments demonstrate that the numerical prediction largely underestimates the failure load for non homogeneous stress states, like in plates with open hole or notches [11].

To overcome this limit, for a reliable numerical prediction of damage we have really to look up to the part scale. An efficient method is to use a “Failure Characteristic Volume” (FCV) that is also very advantageous to avoid meshing sensibility [12]. Accurate results are obtained in multiple configurations (fig. 12).

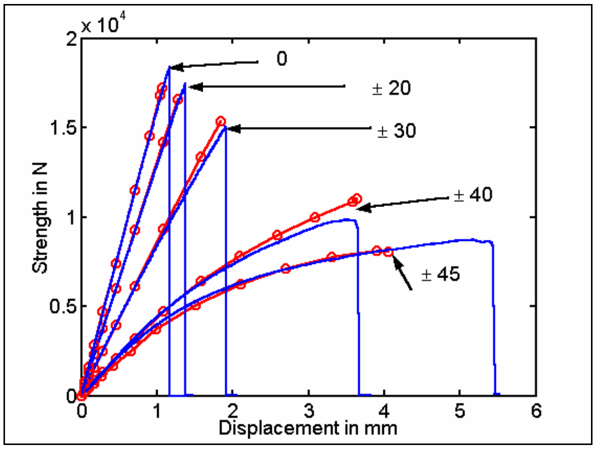

Figure 12 - Comparison between test (——) and simulation (—○—) for a plate with a hole and different laminate lay-up [12]

Moreover these technique coupled with EOD allows to follow step by step the failure process of a part. Especially for laminated composite reinforced with woven fabric, the prediction can be done with numerical tools with a limited complexity. These tools are therefore able to guide the analysis by micro tomography to the areas most relevant by establishing, for each global load assumption, a precise description of the damaged areas. For example a predicted mapping of damage, i.e. crack density, is showed on figure 13. This result, compared with figure 4, clearly shows that the numerical prediction is in good agreement with the experiment.

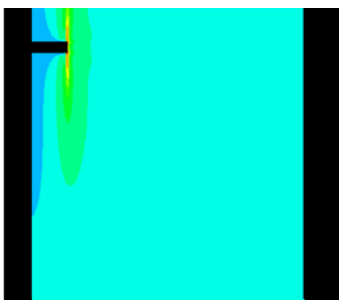

Figure 13 – Predicted cartography of damage (crack density) for a notched composite plate under tension,tension is along the vertical axis, only the left side is presented (courtesy Laboratoire de Mécanique et d'Acoustique, CNRS– Marseille, France)

<u>5.2.3 Convergence of two technologies</u>

Today's advances in two technologies make it possible to envisage from a new point of view the expertise of failed parts. A very effective expertise methodology can thus be developed by a combination of micro tomography and numerical prediction of damage. Its main goal will be to meet the needs of airworthiness and respond to client requests with industrial tools. In this regard it should be emphasized that the over mentioned numerical method for predicting damage, resulting from the work on woven fabric composites, is recognized among the best suited for industry. Similarly, by its very principle of numerical processing, micro tomography is a tool that will take from expertise many of subjective interpretations that are still needed today.

6 - Conclusions

TBD

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