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Review of aeronautical fatigue investigations in France during the period May 2019- April 2021

TECHNICAL NOTE

N° 21-DGATA-1-AT

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Abstract :

The present review, prepared to be published online on ICAF website, summarises works performed in France in the field of aeronautical fatigue and structural integrity, over the period May 2019-April 2021.

Topics are arranged by contributors.

Correspondents who helped to collect the information needed for this review in their own organisations are :

- Manuel De Araujo, Linden Harris and Alain Santgerma for Airbus Operations SAS
- J.C. Ehrström, J. Laye, E. Nizery and N. Bayona-Carrillo for Constellium
- Philippe Gail for Latécoère
- Matthieu Claybrough for Donecle
- Yamina Ouldhammou, Alexandre Guigue, Cyril Pons and Romain Blois for DGA Aeronautical Systems.

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- TABLE OF CONTENTS -

Pages n°

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1. INTRODUCTION AND ACKNOWLEDGMENT

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They will be the right points of contact for any further information on the presented topics.

Many thanks to all of them for their contribution.

2. AIRBUS OPERATIONS SAS

Manuel De Araujo, Alain Santgerma, Linden Harris.

In Airbus Airframe R&T campus located in Toulouse dedicated investigations in the field of Fatigue Testing and Simulation have been focusing in gathering learnings from past experience tests and using this knowledge to maximize the performance of both future physical tests and simulation analysis in order to increase overall test efficiency and tackle early in the development potential issues linked to early crack initiation.

On the physical tests side, investigations are focusing in maximizing learning from a test while improving the test lead time by using smart data acquisition for structure monitoring with the aim of reducing test downtime.

On the simulation test side, a standardization approach is being set with a Large Scale Simulation process that is increasing its validation domain while being compared to Physical Testing. The computational capabilities are used with a large volume of data processing approach allowing to screen the overall structure at a refined level and enabling multi-scale simulation enabling quick to zoom on critical hot-spots. This large scale analysis approach is conducted alongside Validation & Verification process and Credibility Assessment.

While looking at improving fatigue predictions, the fatigue analytical parametric laws and associated fatigue damage models are also investigated to address more complex configurations in terms of loading configuration looking at stress triaxiality and scale effect.

2.1. FATIGUE TEST HYBRID PYRAMID

Structural demonstrations at all different levels of the test pyramid are made of a consistent mix of physical tests and numerical simulation analysis as illustrated here in Figure 1. Smart Simulation and Testing aims at maximizing test data learnings enlarging the design space investigated on the lower half of the pyramid and for the upper half optimizing test lead time with extensive simulation preparation allowing to better focus physical testing effort on more complex areas representation.

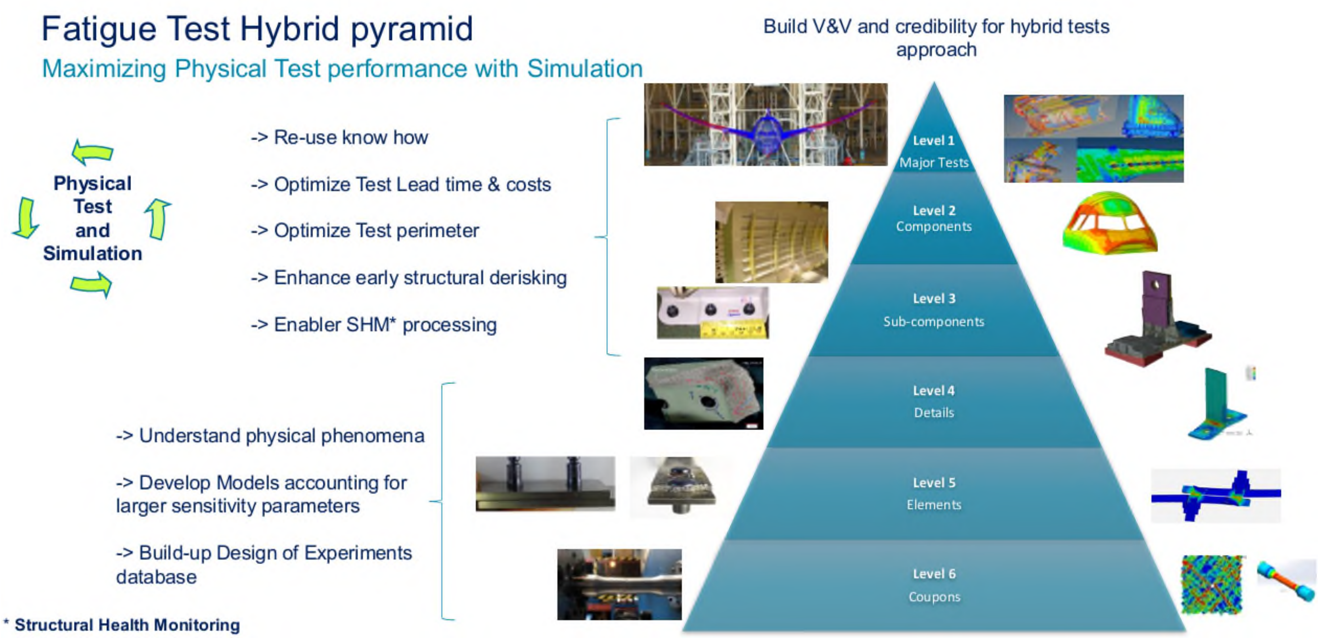


Figure 1: Hybrid Test Pyramid

Physical Test lead time optimization is of interest and live data processing and monitoring are some key investigated bricks that could allow more localized monitoring while enabling to reduce the test downtime linked to our standard means of inspection. In this area Digital Image Correlation with acquisition from on boarded camera devices as shown in Figure 2 on the Test specimen with paint speckling preparation can give this information here in the tested case of a large cockpit specimen Test with cyclic pressure loads. Also investigated Thermal Stress Analysis from thermal cameras acquisition has shown a good potential in monitoring damages pending on relatively quick cyclic loading enabling thermal dissipation measurements.

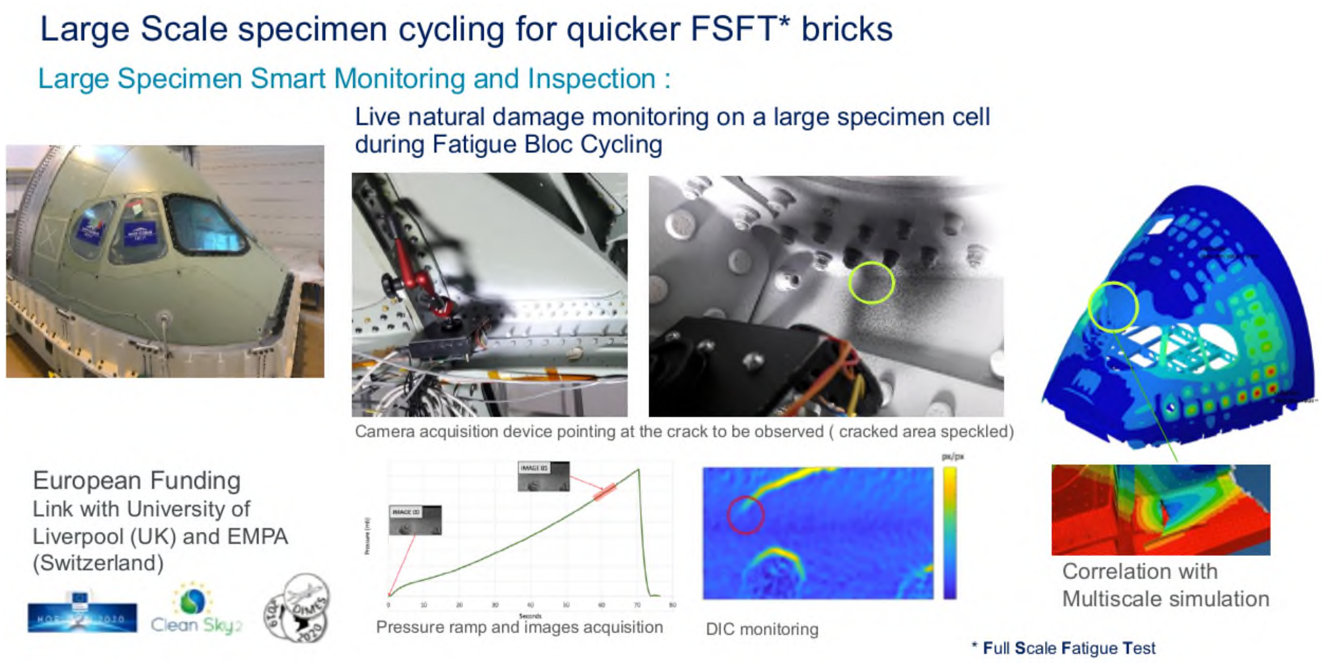


Figure 2: Large Specimen Smart Monitoring

2.2. LARGE VOLUME DATA PROCESSING FROM SIMULATION AND ANALYTICS

See figure 3.

From possible large scale to local test simulation detailing at a local level the necessary good behavioural representation of the structure including details such as of fasteners, the contacts between parts, a standardization of an overall process including Large Scale Model built and data processing framework is aiming at providing an exhaustive hot spot screening of a structure definition at earlier stage in the development.

A data analytics perspective with inputs from Simulations and Physical tests is also investigated to bridge the use of the available data towards two axis, one being the correlation between Physical and Virtual testing, the other being the use of the data across different levels of the pyramid.

This collaborative project around this data framework processing is carried out within the support of French National Funding for Aerospace CORAC involving as partners AIRBUS and EXPLEO.

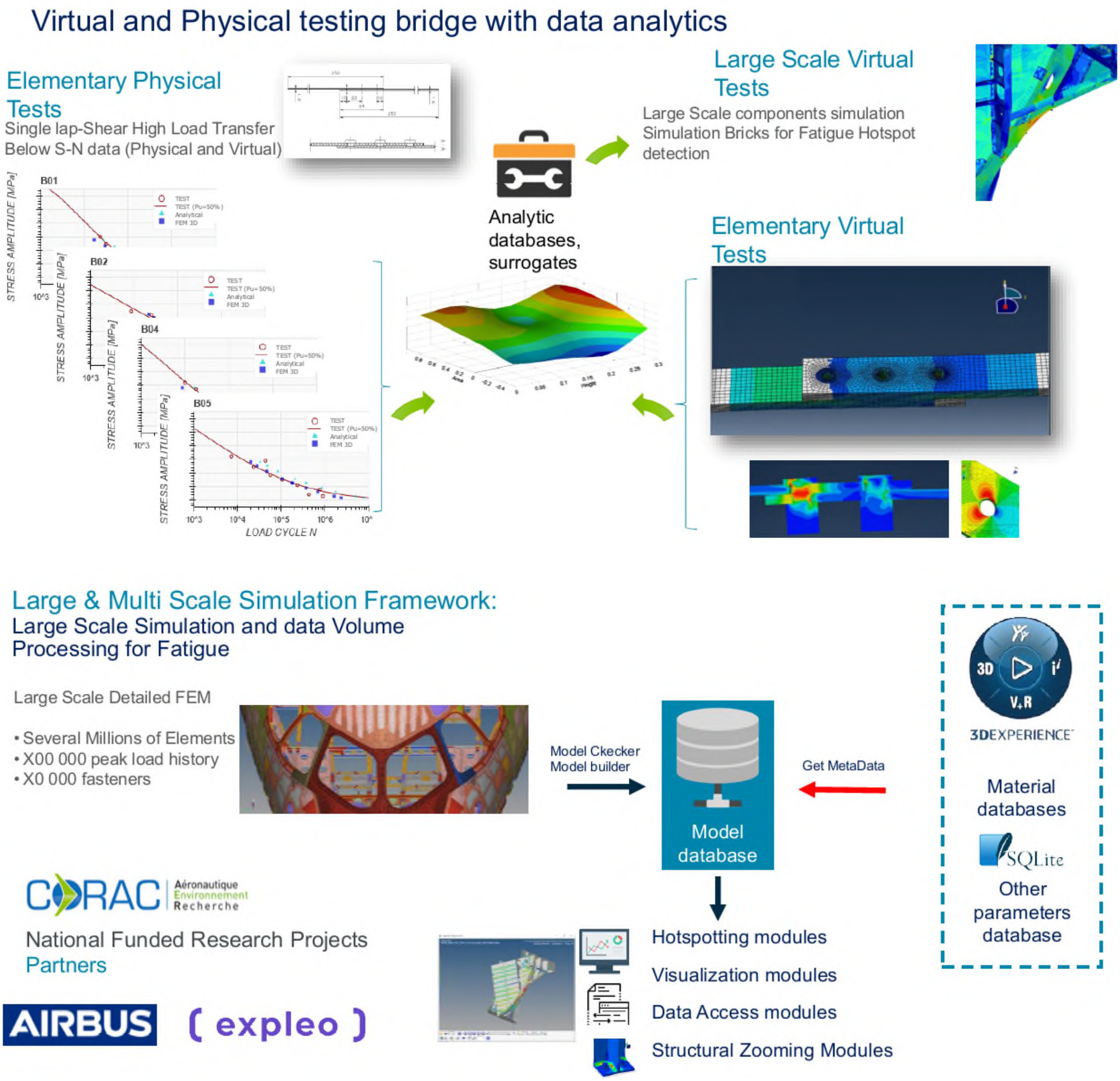


Figure 3: Large and Multi Scale Simulation Framework

2.3. FATIGUE LAW AND FATIGUE DAMAGE MODELS TAILORING

See figure 4.

Fatigue damage idealization either from analytical parametric laws or together with detailed Simulation including Fatigue Damage material modelling is investigated to answer complex structural nodes. In these cases the fatigue model can be adapted to the finer level of information you retrieve from a local 3D simulation and therefore improve your prediction accounting for stress triaxiality parameters and scale effects.

A collaborative project between AIRBUS and the French Aerospace Lab ONERA has been launched under the support of French National Funding for Aerospace CORAC to investigate what specific tailoring is best adapted for better correlation.

Figure 4 : Fatigue Initiation Parameters Investigation

2.4. OUTLOOKS

For Fatigue and Damage tolerance structural evaluation, optimizing and maximizing the overall Test pyramid feedback are made possible with technologies to access and process on a more efficient way the structure data information either coming from physical and simulation testing. This approach therefore requires a significant amount of standardization, verification and validation. With Airbus Large experience over the years on Fatigue and Damage tolerance physical tests, in-service findings and associated analysis, a large information data lake is available to further extract more value from and continue further improving earlier structural maturity.

Taking benefit of a much wider and easier use of efficient multi-scale simulation and structural zooming, specific adaptation of the Fatigue models are also providing a way to reduced prediction gaps.

3. CONSTELLIUM

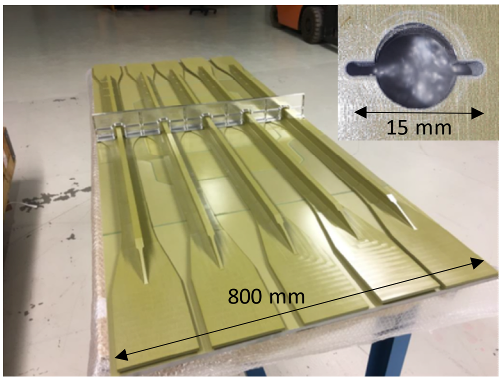
3.1. DAMAGE TOLERANCE OF A HYBRID LOWER WING PANEL

J.C. Ehrström, J. Laye, E. Nizery, N. Bayona-Carrillo

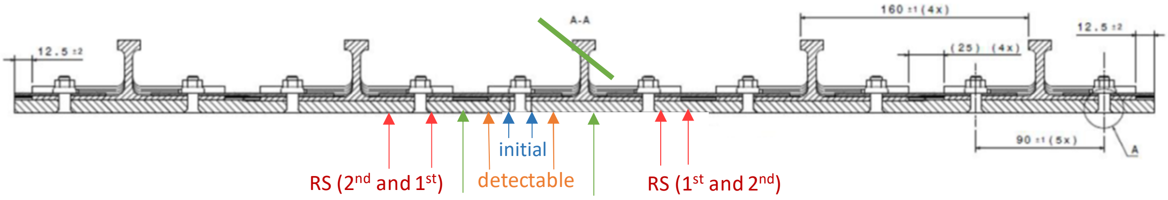
Fiber Metal Laminates (FML) represent a highly damage tolerant (DT) option for lower wing skins that can be included in an advanced high performance metallic wing box. The purpose of the present study is to assess the DT behavior of a panel made of FML with 0.8 mm 2024 T3 sheet, knowing that the current FML materials like Glare® are based on 0.2 – 0.3 mm sheet thickness. Here, 8 metal sheets combined with glass fiber reinforced prepreg interlayers were bonded to make an 8.15 mm thick skin. 2027 T3511 stringers are bonded onto the skin.

The panel was manufactured by GTM in the Netherlands. The test was made at Constellium C-TEC in Voreppe, with the support of Strain Solutions Ltd for crack monitoring by Thermal Surface Analysis and Digital Image Correlation. Constant amplitude loading at a maximum stress of 135 MPa, R=0.1 was applied. This constant amplitude stress represents, in a conservative way, a lower wing spectrum with 90 MPa 1g – stress (details of the justification to be given elsewhere).

The following table and figures illustrate the configuration of the panel, and the sequence of events.



Event	Cycles (total)	Comment
Initial crack: 15 mm (2X 7.5 mm)	0	notches on the sices of a rivet hole
39 mm crack	48000	detectable crack in skin
broken stringer (free flange)	82589	2nd detection event
98 mm on stringer side 62 mm on bay side	181744	Residual strength test up to 234 MPa
102 mm on stringer side 70 mm on bay side	220169	Residual strength test up to 234 MPa



A starter notch was machined in a rivet hole giving an initial defect of 8 mm (rivet diameter) plus a 3.5 mm long notch on each side. Two potential detection events which occurred one after another were identified: a 39 mm crack (more than 1.5 inch); and then a failed stringer characterized by the broken free flange. Either one of the two events could be the start for an inspection interval calculation. In a conservative way, only the second event is considered. 99155 cycles were done before a first residual strength (RS) test (with no significant crack extension during the RS test) and 38425 more cycles before a second RS test (again with no significant crack extension). If the second RS test is considered, a >45000 flight inspection interval can be derived from the test with a safety factor of 3 ((220169 – 82589)/3). The RS test was performed up to 234 MPa (test machine limit). This corresponds to a 93 MPa 1g – stress with a ratio of 2.5 between the 1g – stress and the limit load.

The present results validate the assumption of a ~90 MPa 1g – stress for a FML panel with 0.8 mm sheet thickness. The corresponding stress allowable increase versus a 2024 T3 bulk panel is ~20%, as 75 MPa is a relatively high 1g – stress for 2024 T3. In addition, the density benefit is approximately 5% for the skin versus a bulk 2024; 5% density benefit would also be obtained on the stringers by replacing 2027 by an Airware® Al-Cu-Li alloy.

4. LATECOERE

4.1. DEPACE & ARCHES PROJECTS : MONOBLOCK METAL DOOR

Ph. GAIL (Latécoère), Y. OULD HAMMOU (DGA Aeronautical Systems)

LATECOERE is a major aerostructures designer and manufacturer. Its innovation R&T department is involved in several research programs on products, materials and processes.

The complexity of the current metal door architectures assembled with more than 150 pieces and 1500 fixings led LATECOERE, R&T to a major innovation : a passenger door structure made from forging, stamping and machining processes to get a monoblock structure.

The benefits researched are cost savings (RC, NRC), solution suitable for high volume, structure with native functions.

The solution had to be validated by:

- Control of residual stress
- Demonstrator manufacturing
- Scale 1 mechanical test

The scale 1 monoblock door demonstrator door is the result from two innovation programs : DEPACE and ARCHES.

PAX DOOR FATIGUE TESTING

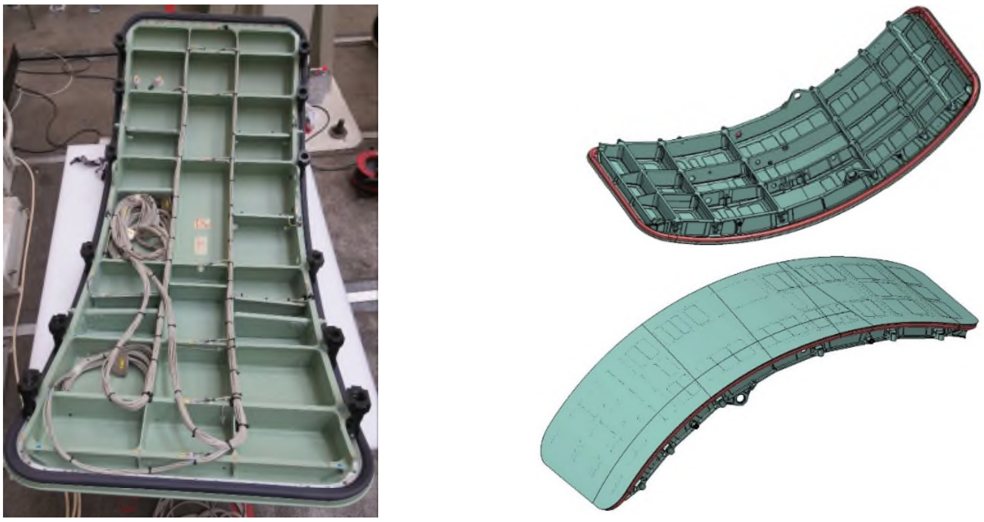
The goal of these tests is to validate the behavior of the demonstrator of the ARCHES monobloc door, and to correlate its behavior with numerical simulations, under pressure loading according to certification conditions (fatigue cycling and static loads).

The ARCHES door demonstrator (see test specimen in the figure below) is representative of the complete geometry of the ARCHES door, without structural modification. It is mounted on a test frame making it possible to simulate both the conditions of deformation of the door frame of the aircraft fuselage and the cabin pressure applied on the door.

The different points that LATECOERE plans to verify by this test on a scale 1 demonstrator are as follows :

- Fatigue resistance (cycling under fatigue pressure).
- Damage tolerance (monitoring of artificial defects and detection of natural defects).

- Structural strength at limit load and at ultimate load.
- Search of the failure load.



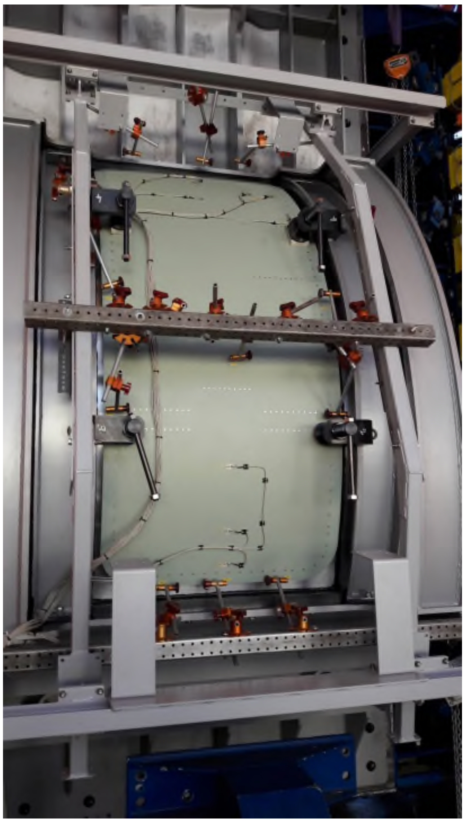
Test Specimen

TEST RIG

The test frame to simulate both the deformation conditions of the aircraft fuselage door frame and the cabin pressure applied on the door was designed and produced by DGA TA from a pre-existing test facility called MESSIR (Means of Testing of Representative Innovative Structures). MESSIR is a means of testing single curvature panels subjected to multiple stresses (mechanical, pressure, thermal).

The aim and main challenge were to design a large dimension tooling, fulfilling the very tight tolerances set out in the LATECOERE specifications and able to introduce loads with the high accuracy (pressure and displacements) requested by LATECOERE.

The pictures below show details of the test rig and specimen in test installation.



Test rig and test specimen in test installation for a 3D positioning check

LOADING

The main challenge related to loading for this test was manage to synchronize the application of millimetre range displacements at door stop through actuators with the application of pressure. This challenge was successfully taken up thanks to DGA Aeronautical System knowhow in complex loading systems.

5. DONECLE

5.1. AUTOMATIC UAVs FOR AIRCRAFT INSPECTIONS

Matthieu Claybrough

Improving aircraft life extension and life management support is a crucial issue for any aircraft operator, and thus for the Air Force and DGA. For safety reasons, every aircraft undergoes many maintenance operations and pre-flight checks during their life time. In particular, visual inspections play a key role. The strict damage tolerances require heavy equipment such as mobile elevating platforms to reach positions from where aircraft mechanics can properly observe the exterior surface.

To improve the overall maintenance cycle and increase safety, the French company Donecle, has developed automated UAVs that are capable of fully inspecting civil and military aircrafts 20 time faster than current methods.

This drone flight is completely automated, with no remote control or backup pilot required. Each inspection captures hundreds of high-definition images that are transferred to a tablet from which a software can be used to generate reports automatically and check aircraft history of past inspections.

The UAV is equipped with a laser positioning technology, that enables safe, automatic flight with centimetric accuracy in both indoor and outdoor conditions. Navigation sensors ensure safe operation by preventing collisions. All sensors are on-board and the system does not need GPS, beacons or other external installation – key for easy deployment in any hangar or site. The drone can inspect up to 1 square meter per second, leading to full inspection times under 15 minutes for a fighter jet or 45 minutes for AWACS or ATL2 aircrafts for example.

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Throughout the inspection the drone is capturing high definition pictures with a camera on an embedded gimbal. The forward mounted gimbal can acquire pictures in all directions, enabling full inspection of lower surfaces, such as the aircraft belly, under the wings, engine nacelles, etc. The low-profile drone can even fly under most fighter jets. A powerful flash system guarantees consistent and repeatable image quality, day or night, independently of any hangar lightings. A sampling resolution exceeding 10pixels per square mm and a carefully calculated overlap ensures that each potential defect is visible on multiple images and can be precisely identified anywhere on the aircraft.

The image quality is deemed equivalent or superior to an inspector working at arms distance. For example, the system can be used to detect possible defects and damages such as corrosion (Figure 1), Erosion (Figure 2), lightning burn (Figure 3) or paint defects.

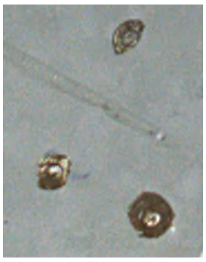


Figure 1 Corrosion

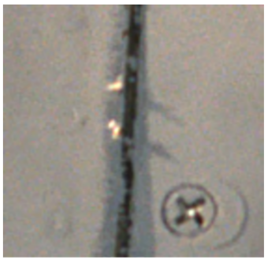


Figure 2 Corrosion

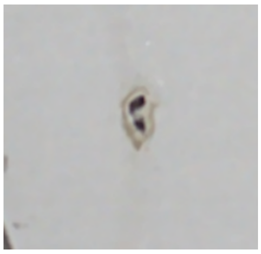


Figure 3 Lightning burn

To further speed-up the process and help the human inspectors, the company has deployed artificial intelligence algorithms to detect the most common defects. A first step was to have thousands of images annotated by experts in order to provide a large dataset required to train machine learning methods. The automatic visual inspection relies on the use of a *Deep Neural Network (DNN)* as object detector. However, using such a network with high-definition images does not allow very small objects classification (less than 1 mm^2) in reasonable time whereas those objects are crucial as they can be critical defects (lightning burns). Therefore, the company implemented a two-stage method that relies on the use of two neural networks: a first one for fast defect detection using downsized images, and second one for defect classification using extracted regions of interest in full resolution. All potential defects (small or ambiguous objects) are gathered for a supplementary classification step and can be further inspected by a human inspector if the system is not confident enough.

Addressing the defect recognition as an image classification problem allows the use of advanced techniques that are much more complex to introduce into a one-step object recognition algorithm in which detection and classification are inseparable. Deep Learning based approaches have proven to be very effective when a sufficient amount of data is available for each desired class.

The proposed method performs better than state of the art model (YOLOv3) for this application, with impressive probability of detections (PoD) and detection rates for common damages such as corrosion, erosion and lightning burns.

This technology has been successfully trialled on multiple aircraft, both commercial and military and is now being deployed on multiple inspection programs. The image quality has already been qualified for different applications, whilst the automatic visual inspection algorithms are still being studied. Theoretical guarantees and extensive trial campaigns are on-going in order to qualify such technology.

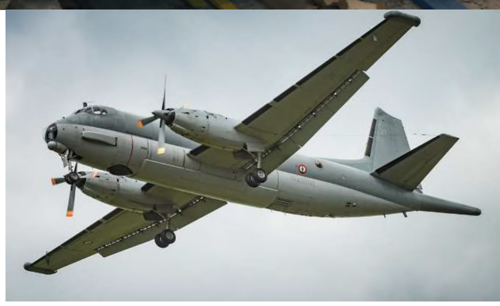
Moving beyond visual inspection, Donecle has recently equipped an automatic drone with a 0.1mm dent detection 3D scanner. This novel technology should further enhance visual inspection with detailed surface assessments and measurements. As sensors and machine vision algorithms improve, one can bet that the digital twins created by the drones will help in assessing the overall airframe integrity, increasing safety and repair planning efficiency. Last but not least, the digital history will help in further tracking damage trends, structure evolutions, and generally speaking improve our understanding of how airframes age overtime.

6. DGA AERONAUTICAL SYSTEMS

6.1. ACCROCS PROJECT

Alexandre Guigue

Atlantique 2 (ATL 2) is an aircraft operated by the French Aeronaval (Navy) forces. Its uniqueness comes from its outer wing composition : an aluminium sandwich material. If this material provides a good bending stiffness over weight ratio, corrosion might be found between the skin and the core of this material close to wing ribs and spars. In order to anticipate debonding, to track and repair the potential damages, French maintenance workshops in collaboration with DGA TA issued a maintenance schedule from coupon testing.



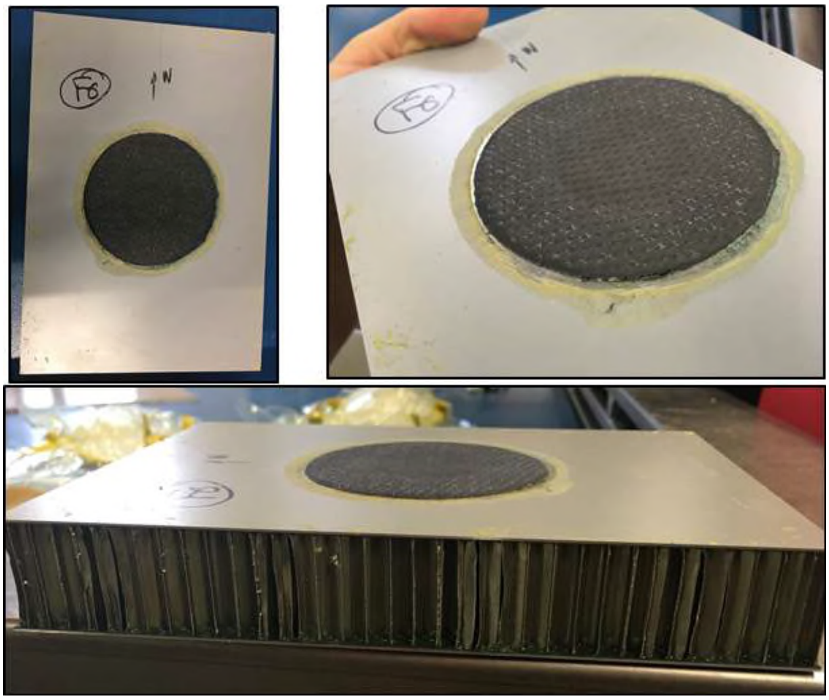
Up : ATL 2 outer wing at DGA AS facility. Down : ATL2 in flight

DGA AS suggested further testing from an complete wing. The objectives consist in a better knowledge of debonding propagation on a 3D full scale structure while introducing a global scale load. This also enables DGA TA to maintain and improve its knowledge in such large-scale testing, mixing instrumentation such as Digital Image Correlation, gauges and acoustic and perfect numerical model and testing correlation. The test hence consists in comparisons between undamaged, damaged and repaired panels from different methods.

DGA AS designed the test set up that simulates at the laboratory Atlantique 2 outer wing flight loads. This includes limit conditions applied on the outer wing similar to the ones on the airplane. An interface between the wall on which the wing is attached and the wing was selected and designed. Six actuators will introduce the defined loads on a three wing clamp jig.

The first challenge is to introduce a damage on the wing, reproducing a corrosion damage. A pre study was carried out in a joint program with ISAE Supaero students highlighting a method that would overheat the glue that keeps together the skin and core of the sandwich panel.

Post mortem control of the heating method on a coupon



Composite repair on a coupon

The second challenge was to define the type of zones to investigate, damages representative to the observations on aircrafts and repairs of interests. In this study, usual and composite repairs are carried out and compared.

Tests have not started yet. They will include pre static loading to refine the setup. A fatigue phase then will follow for an aircraft life. Ultimate load tests will be carried out at last. Between all phases, non-destructive inspection is planned to monitor the evolution of the structure damage.

Finally, this test will enable DGA TA to gain knowledge in 3D structure evolution of corrosion like damages on sandwich panels. This will help Maintenance Workshop to anticipate the repairs with better design.

6.2. RANDOM VIBRATIONS FATIGUE ANALYSIS AND TESTS

Cyril Pons

DGA is in charge of qualification aspects and continued airworthiness for military aircrafts. In this context, DGA have to perform tests for the qualification of equipment in vibrations environment. But tests are expensive and can take a long time to perform, relatively to operational issues. The objective of this study is not to replace all the tests by calculations – many data can only be obtained by test for now, damping for example – but to be able to anticipate a test in order to reduce hazard of non-predicted failures or to extend a structural qualification from a vibrations environment substantiated by test to another one lightly different. Moreover, some subjects are raised about crack initiations which cannot be explained by “classical” fatigue models, especially for rotorcrafts, because of the type of excitation: vibrations. So, with this study, DGA could also improve its knowledge about vibration fatigue in order to explain and to bring solutions to in-service occurrences relative to this particular subject.

Indeed, vibrations environments are characterized by low stress levels, high frequencies (many fatigue cycles) and sometimes random spectra. These characteristics lead to some analysis difficulties: to get an initiation with low stress levels and to be able to count cycles for random spectra. The aim of this study was to improve DGA knowledge about random vibrations fatigue by evaluating some specific models from literature. They were assessed by two different approaches: numerical and experimental on coupons. The objective was to answer to some questions such as: is the model accurate? Is it conservative? How many parameters are needed? Another part of this study was about the ability of using this model for real structure.

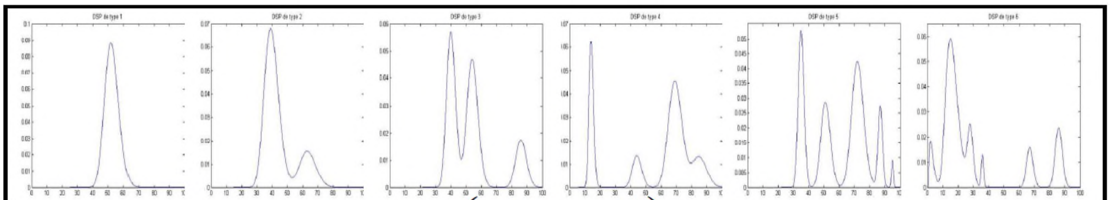
Damage calculations for random vibrations environment are based on "classical" damage calculations. The main difference and difficulty is the way to "count" cycles, because cycles don't exist anymore. So, it is needed to estimate a probability density function of stress from the power spectral density of the excitation.

$$E[D] = \int \frac{S^b}{C} . E[P]. f_s(S)\, dS$$

- $f_s(S)$ represents the probability density function of having extracted from the signal an elementary cycle with an amplitude S.
- $E[P]$ is the average number of peaks of the signal per unit of time.
- $\frac{S^b}{C}$ represents the damage of an S amplitude cycle when the Basquin model is used to approximate the S-N curve.

The different models from literature give different probability density functions. The first one, the Narrow band model, is purely theoretical and well none but, as its names suggests, it isn't adapted to wide band signal. The other models are split in two types. The first ones are based on the Narrow band model: they add a corrective factor, which is often empirical, to correct and improve the Narrow band model. The second ones are direct models.

The numerical assessment of these models was made by comparison with "classical" damage calculations. More than 600 power spectral densities were generated at random on the [0 ; 100] Hz band.

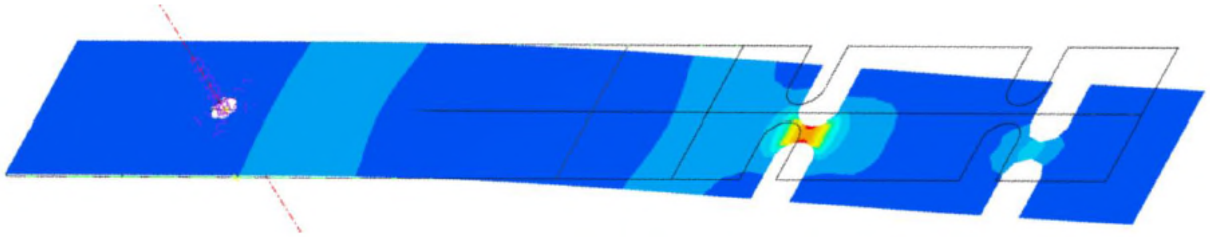


$$S(f) = \sum_{i=1}^{n} A_i \times \exp\left(-\frac{(f - f_{ci})^2}{B_i}\right) \quad with \;\; n = 1..6$$

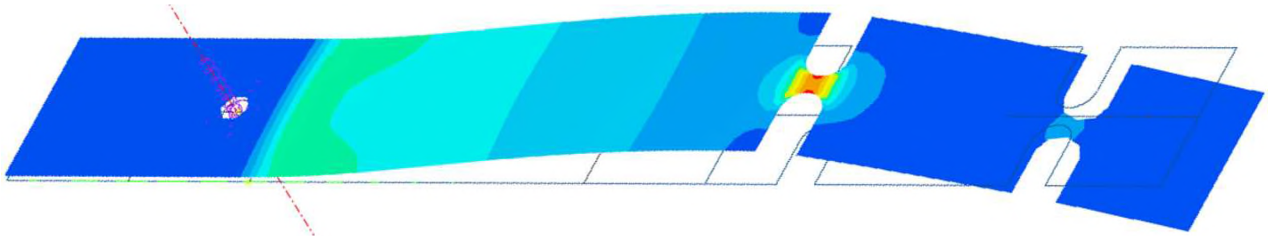
For each one, many corresponding temporal signal were also generated then the damage was calculated for each signal by "classical" method (Rainflow counting and Miner's rule were used). The average of all these calculations (for each power spectral density) was the reference. The damage was also calculated directly from the power spectral densities with the different previous models. A comparison of the results led to assess their accuracy, scattering and conservatism.

The aim of the second part of the study is to assess these models by confronting them to test results: some tests are done with a vibrating pot on a coupon. To be able to assess properly the models, the coupons had to be "wide band". Indeed, the standards for aircraft and rotorcraft, which were study in the frame of this work, present generally random vibrations on a wide band and some typical frequencies excitations corresponding to rotor or blades speed. In fact, a wide band response for "simple" coupon was quite difficult to obtain, that is why it was designed to obtain a transfer function with two natural mechanical frequencies. The coupon was found in literature and has only one critical point.

1st resonant frequency



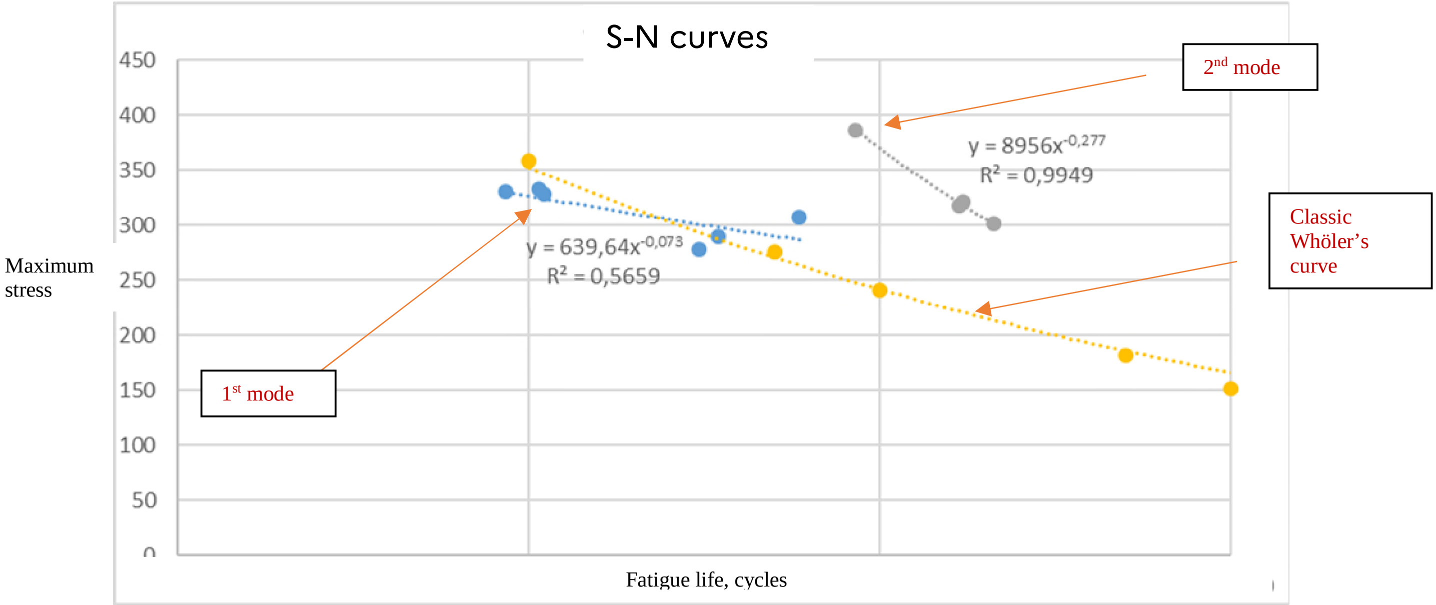
2nd resonant frequency



This optimization and the random excitation definition were made thanks to finite elements modelling (FEM) of the coupons and damage calculations with the different previous models.

In order to get more accurate results, a huge test campaign has begun on 100 aluminum 2024T3 coupons. This material has been chosen because it is the most commonly used material in aircraft industry.

17 coupons have been used to define the material behavior in order to adapt the numerical model. We applied sinusoidal spectras on first and second resonant frequencies at 17 Hz and 85 Hz. The results shows that the S-N curve is dependent on the excitation frequency as we can see on the following graph :



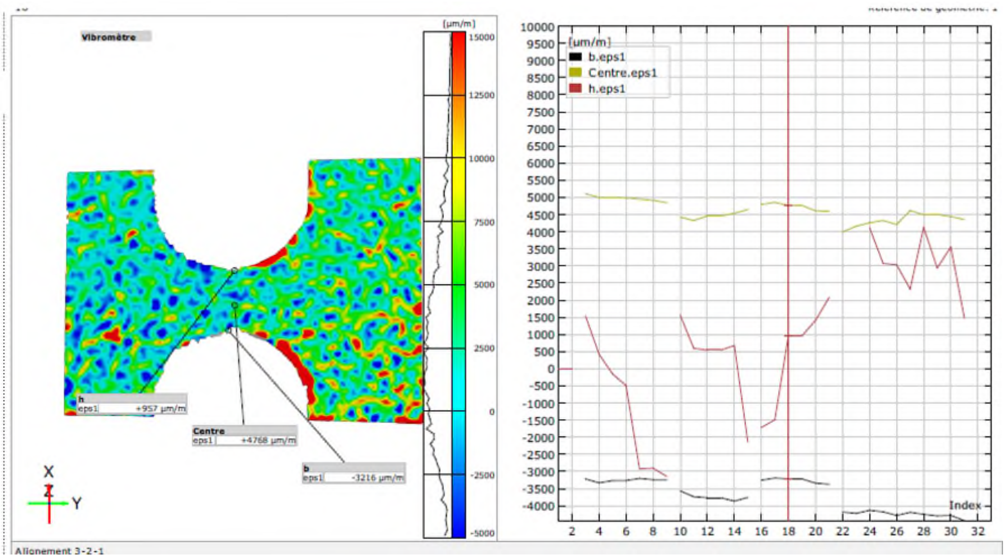
The coupon is broken for a larger number of cycles for the 2nd mode at the same level of stress measured. That result was not expected that is why complementary tests have been carried out.

A thermal measure has been done on the two different frequencies and showed that there is no heat in the coupon created by the excitation during tests.

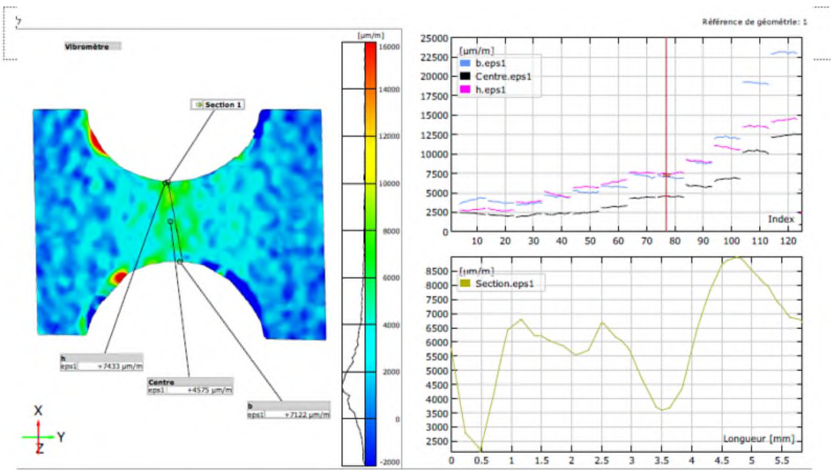
Finally, a digital image correlation has been carried out as we can see on the following picture. It was the first time that a digital image correlation was done on a vibration pot at DGA Aeronautical systems.

Digital image correlation test at DGA Aeronautical systems

The strain measures were impossible at 17 Hz. Very important noise did not enable to have the strain profile. However, we had better results on the second resonant frequency at 85 Hz. We can see the strain profile and its changes during the fatigue test.



1st mode: 17 Hz



2nd mode: 85 Hz

The lack of results on the 1st mode did not allow us to compare the two strain profiles.

Other tests will be done on the 1st resonant frequency in order to compare strain profile between the two modes. It will help understanding the difference in the S-N curves.

After that, 30 coupons will be used to see the consistency between tests and calculation on random vibration fatigue. Many vibrational spectra will be tested on coupons.

These results will also be compared with calculation using Vibration Fatigue module on Ncode software.

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