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REVIEW OF AERONAUTICAL FATIGUE INVESTIGATIONS IN FRANCE DURING THE PERIOD MAI 2021- JUIN 2023

TECHNICAL NOTE

N° 23-DGATA-ST-ICAF2023-V1F

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TECHNICAL NOTE
N° 23-DGATA-ST-ICAF2023-V1F

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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 2021-Juin 2023.

Topics are arranged by contributors. Correspondents who helped to collect the information needed or to allow the dissemination for this review in their own organizations are:

- Manuel De Araujo, Alain Santgerma, Sébastien Amiable, Jérôme Rousset and Geoffrey Veragen for Airbus Operations SAS; Ben Ogborne for AIRBUS Operations Limited, UK
- J.C. Ehrström, M. Bellavoine, E. Nizery and N. Bayona-Carrillo for Constellium
- Richard Nguyen, M.Durand for Dassault Aviation
- Jean-Rock Augustin, Yamina Ould hammou, Alexandre Guigue, Damien Collin and Nicolas Pommepuy for DGA Aeronautical Systems.
- Robin Tanquerel, Matthieu Claybrough and Adelaïde Poisson for Donecle
- E. Paroissien, F. Lachaud and S. Schwartz for Institut Clément Ader (ICA), Université de Toulouse, ISAE-SUPAERO, INSA, IMT MINES ALBI, UTIII, CNRS, Philippe Gail for Latécoère
- François-Xavier Fraisse, Marc Gravil, Fabrice Robert and Arnaud Vuillet for Safran Aerosystem
- Pascal Bro for Safran Landing System

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1. INTRODUCTION AND ACKNOWLEDGMENT

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- Pascal Bro for Safran Landing System 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. FULL-SCALE STRUCTURAL AND COMPONENT FATIGUE TESTING

2.1. Review of aeronautical fatigue investigations in France for Airbus Operations S.A.S: Hydrogen Tank Fatigue investigation in cryo environment

Manuel De Araujo

2.1.1. Introduction

For the next generation of Zero Emission aircrafts powered with hydrogen, the tank structure is a complex structural equipment for which important investigations have been launched in Airbus. The operational thermal range of such structures will vary between Room Temperature and cryogenic temperatures down to 20K for LH2 (Figure 1).

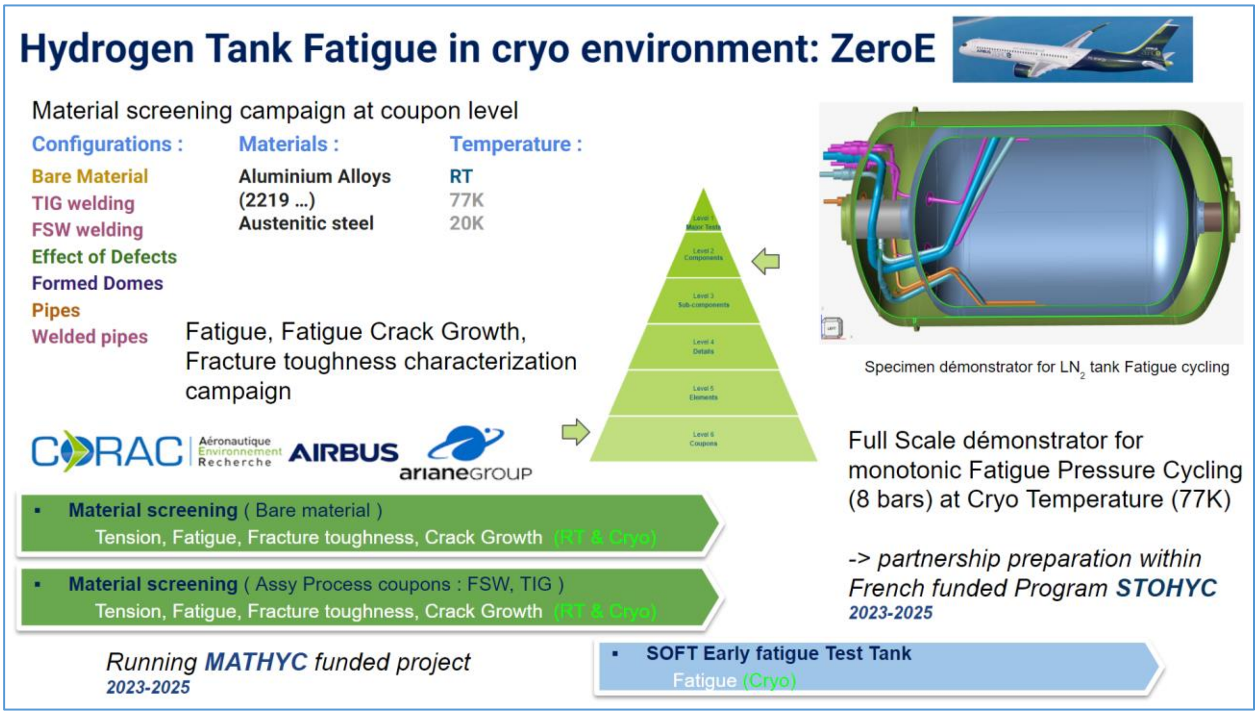
For structural integrity a specific attention has been paid to Fatigue substantiation of a metallic Tank involving a wide range of key disciplines such as thermodynamics and thermal analysis in order to understand the behavior of such structure during its operational life.

A starting point is being investigated at low pyramid level with standard coupons characterization of Bare Material adding also weld processed coupons typical of design solutions investigated such as TIG welding and Friction Stir Welding. These mechanical characterizations will cover Fatigue stress-Life, crack growth and fracture toughness experimental data curves in different thermal environments : Room Temperature, 77K (in LN2 environment) and down to 20K (in LH2 environment).

For the cryogenic tests requiring some specific Testing environment a partnership between AIRBUS and ARIANE Group to cover this extensive low pyramid test campaign has been set within CORAC French Funded Program (MATHYC Project) taking benefit of the ARIANE Group Test facilities and experience for such tests.

Also looking at upper level of the structure Test pyramid a Full scale Test tank is being defined for monotonic fatigue cycling with LN2 tank fill to test such tank structure embedded with characteristic welded junctions to be cycled with Monotonic fatigue cycling, the objective being an early learning for metallic Fatigue behavior under these conditions. This Test is also part of CORAC Funded project STOHYC.

2.1.2. Test pyramid presentation



Hydrogen Tank Fatigue in cryo environment: ZeroE

Material screening campaign at coupon level

Configurations :	Materials :	Temperature :
Bare Material	**Aluminium Alloys**	**RT**
TIG welding	**(2219 …)**	**77K**
FSW welding	**Austenitic steel**	**20K**
Effect of Defects		
Formed Domes		
Pipes		
Welded pipes		

Fatigue, Fatigue Crack Growth, Fracture toughness characterization campaign

Specimen démonstrator for LN_2 tank Fatigue cycling

Full Scale démonstrator for monotonic Fatigue Pressure Cycling (8 bars) at Cryo Temperature (77K)

-> partnership preparation within French funded Program ***STOHYC***
2023-2025

- **Material screening** (Bare material)
  Tension, Fatigue, Fracture toughness, Crack Growth (RT & Cryo)
- **Material screening** (Assy Process coupons : FSW, TIG)
  Tension, Fatigue, Fracture toughness, Crack Growth (RT & Cryo)

Running ***MATHYC*** *funded project*
2023-2025

- **SOFT Early fatigue Test Tank**
  Fatigue (Cryo)

Figure 1: Hydrogen Tank Fatigue investigation in cryo environment.

2.2. Improvement of knowledge in Control, coROsion and mechanical behavior of ATL2 Structures: ACCROCS (Amélioration des Connaissances en Contrôle, coROsion et comportement méCanique des Structures d’ATL2) – DGA TA

A.Guigue

Atlantique 2 (Figure 1) is an aircraft operated by the French Aeronaval forces. Its uniqueness resides in its outer wings composition: an aluminium material sandwich. If this material provides a good bending stiffness over weight ratio, corrosion has been found between the skin and the core (disbonding) of this material close to wings ribs and spars. French maintenance workshops, in collaboration with DGA TA, issued a maintenance schedule in order to anticipate debonding, to track and repair the potential defaults on the fleet.

Figure 1: ATL2 in flight

DGA TA, a large-scale structure-testing centre, suggested further testing from an entire wing. The objectives consist in a better knowledge of debonding propagation on a three-dimension structure while inputting a global scale load.

This enables DGA TA to maintain its knowledge in full-scale testing, mixing instrumentation such as large window Digital Image Correlation (DIC), strain gauges, Fiber Bragg Grating and large displacement camera measurements.

Novel fractal speckle images techniques[1] (Figure 2) are used to track the disbonding propagation of the extrados sandwich panel while moving into the test setting.

Figure 2: Left : Example of DIC placed on an area of interest on the wing. Right: Wing extrados and gauges wires

DGA TA experts fully designed the mechanical test that recreate inside a test hall, Atlantique 2 outer wing limit loads. The test involves bending an outer wing upwards and compares behaviours between sane, deficient and repaired extrados panels (Figure 3).

DGA TA team set these precise areas of study across symmetrical parts of the wing and alternatively close to stiff elements such as ribs and spars. Six actuators divided in three wing clamps were set in order to input the representative bending loads on chosen areas.

An interface between the wall and the wing was also designed by DGA TA team in order to represent correct boundary conditions.

Figure 3: Test setting. Left : overall view, Right : DIC setup including darkroom preventing parasite reflections from the outside

After a pre study carried in a joint manner with ISAE Supaero, overheating technique was performed on sandwich wing panels area of interest to introduce maximum allowable defects as defined in the maintenance plan. Maximum defect sizes was defined by test coupons.

Some of these defects were repaired as defined in the maintenance plan and performed by French maintenance workshop. A composite repair was designed and realized on the wing to be compared with usual aluminium repairs.

---

[1] Raphaël Fouque, Robin Bouclier, Jean-Charles Passieux, Jean-Noël Périé. Fractal Pattern for Multiscale Digital Image Correlation. *Experimental Mechanics*, 2021, 61, pp.483-497. doi: 10.1007/s11340-020-00649-7. hal-02982126v2.

At first 20% of limit load static loading was performed to refine and to prepare the test setup by bridging the clearance gaps and troubleshoot main issues. This was followed by a 60% limit load static loading to get familiar with wing behaviour and troubleshoot large load inputs.

For this load case, vertical deflexion was close to the meter. A fatigue phase follows and represents the equivalent of an aircraft life. DIC shots will be made along the test in order to highlight the disbonding propagation while gauges will track strain evolution through every test phases.

Finally, extreme load tests will be carried and wing rupture will be achieved. Between all phases, non destructive controls are planned to acquire the evolution of the structure damage.

This test will enable DGA TA to gain knowledge in evolution of corrosion on 3D structures like damages on sandwich panels, improve correlation skills between numerical model and testing through gauges and large window fractal DIC methods. This will help Maintenance Workshop to anticipate the repairs and better appropriate the aircraft.

---

[1] E. Paroissien, F. Lachaud, S. Schwartz (2022) « Modelling load transfer in single-lap adhesively bonded and hybrid (bolted / bonded) joints», Prog Aerosp Sci; 130:100811.

2.3. Fatigue tests of hook and landing gear doors rafale aircraft

D.Collin (DGA TA), N.Pommepuy (DGA TA)

These tests contribute to an overall on-going effort to significantly extend the life of the Rafale system beyond its initial design life, through determination of the maximum intrinsinc capabilities of components, while reducing programmed maintenance tasks or early replacement of parts.

Testing on components are being prepared at DGA Aeronautical Systems Testing Facility to significantly extend the life of the Rafale system.

The tests will use a complex spectrum derived from the airplane operational use to evaluate the initiation and growth phases of cracks (if it occurs) and finally, to assess the residual strength of the components.

Each test requires a specific test rig as well as a specific set up of hydraulic jacks (Figures 1 & 2). After the tests, NDT will be realized and fracture surfaces will be analyzed.

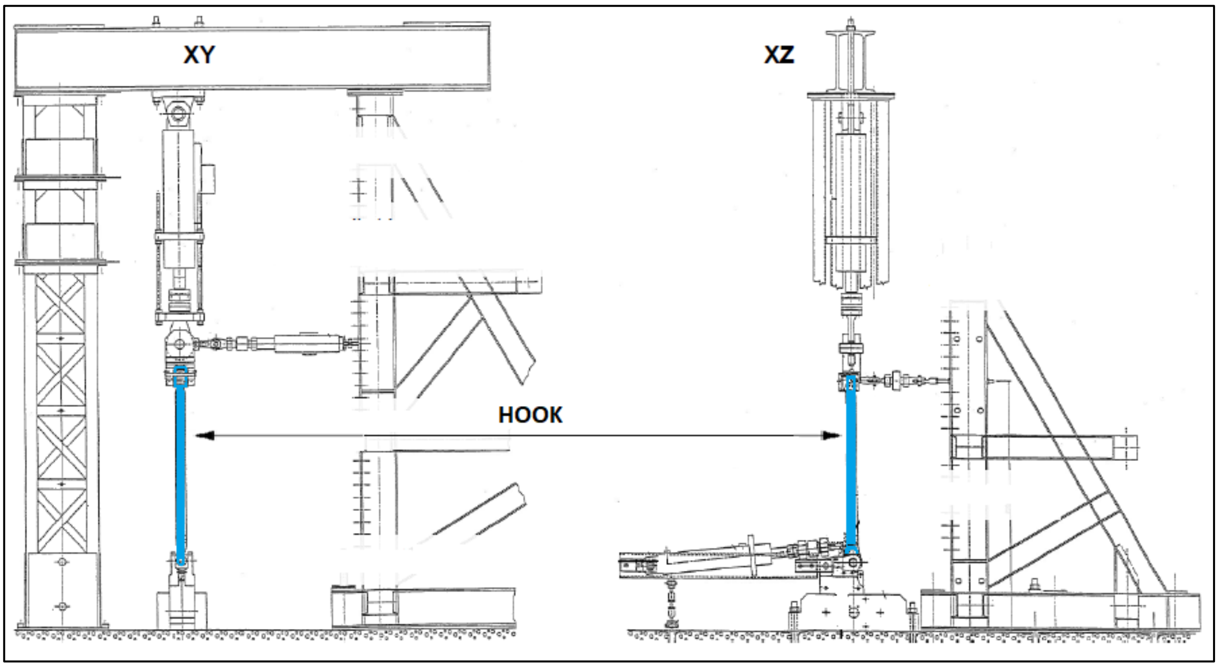


Figure 1: Rafale hook in the test rig

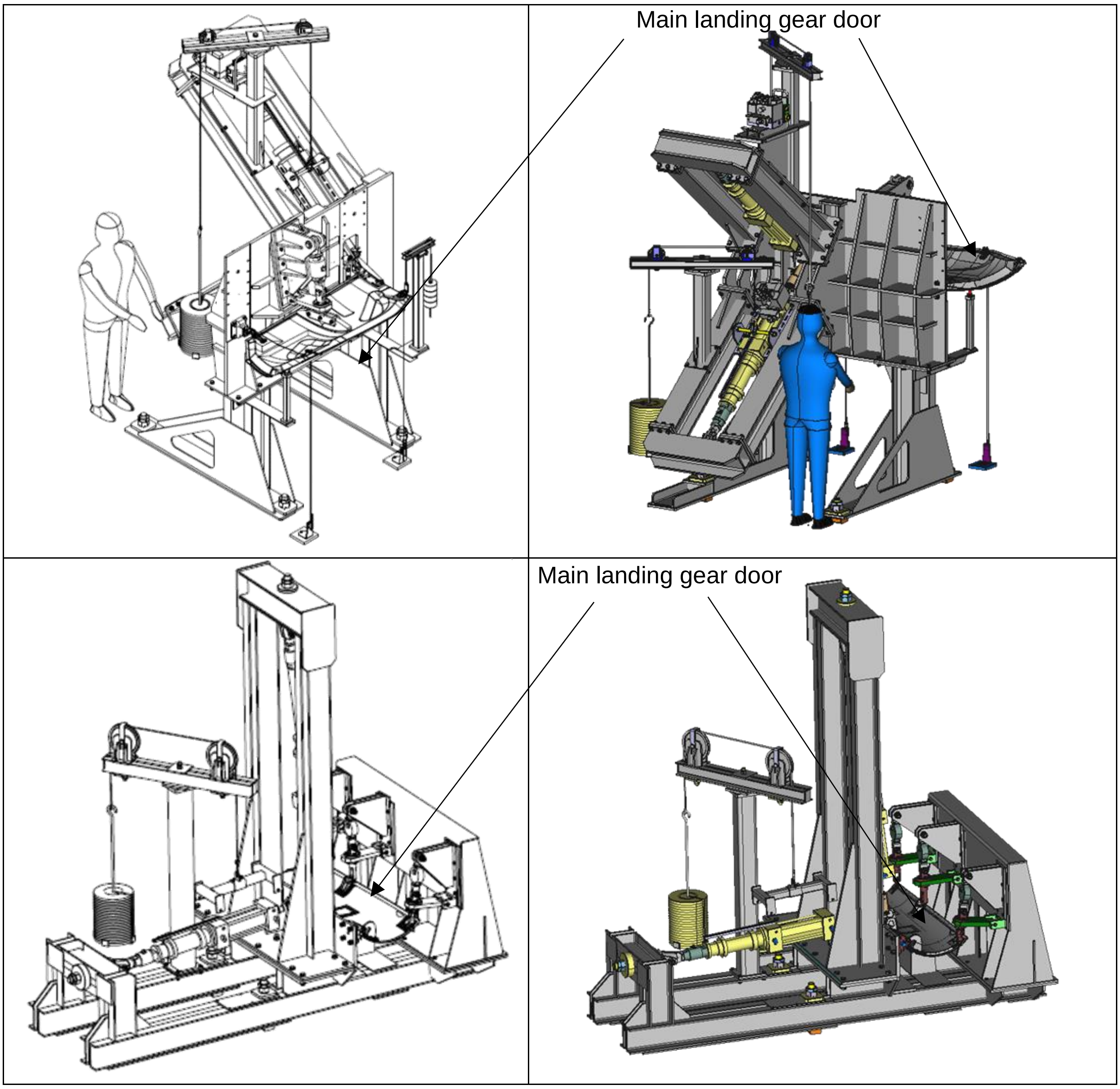


Figure 2: Test rig for the Rafale main and nose landing gear door

Both components will be equipped with strain gauges and displacement sensors.

2.4. Description of fatigue tests for Mirage 2000 Main Landing Gear (MLG) and Nose Landing Gear (NLG) - DASSAULT / SAFRAN AND DGA

N.Nguyen (Dassault Aviation), P.Bro (Safran Landing System), Y.Ould Hammou (DGA TA)

Testing on Mirage 2000 MLG and NLG are in progress at DGA Aeronautical Systems Testing Facility in the frame of the mid-life upgrade (Figures 1 & 2).

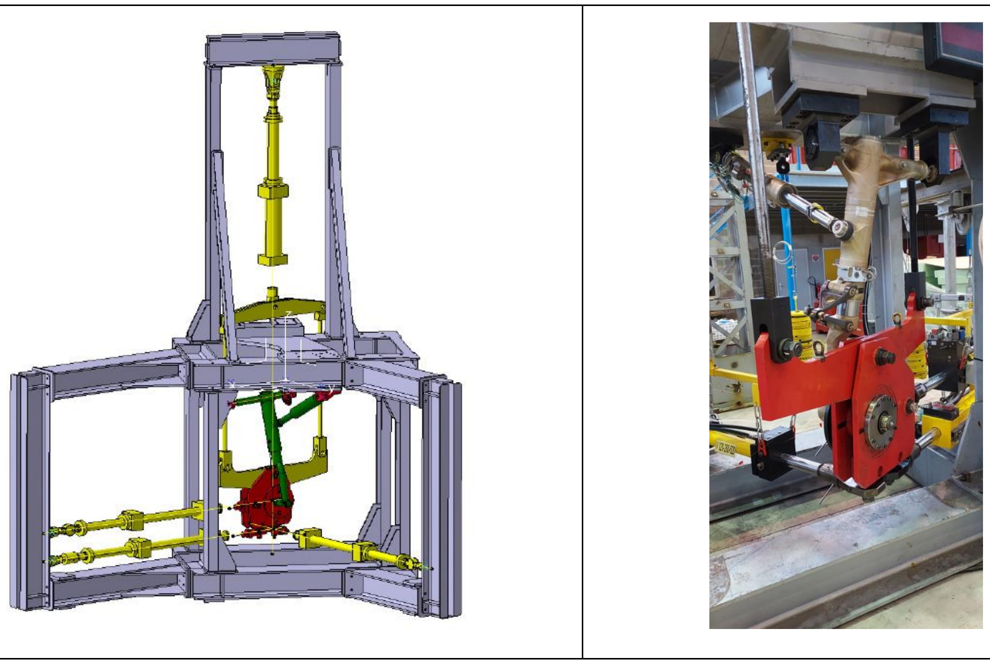


Figure 1: Test rig for the M2000 main landing gear

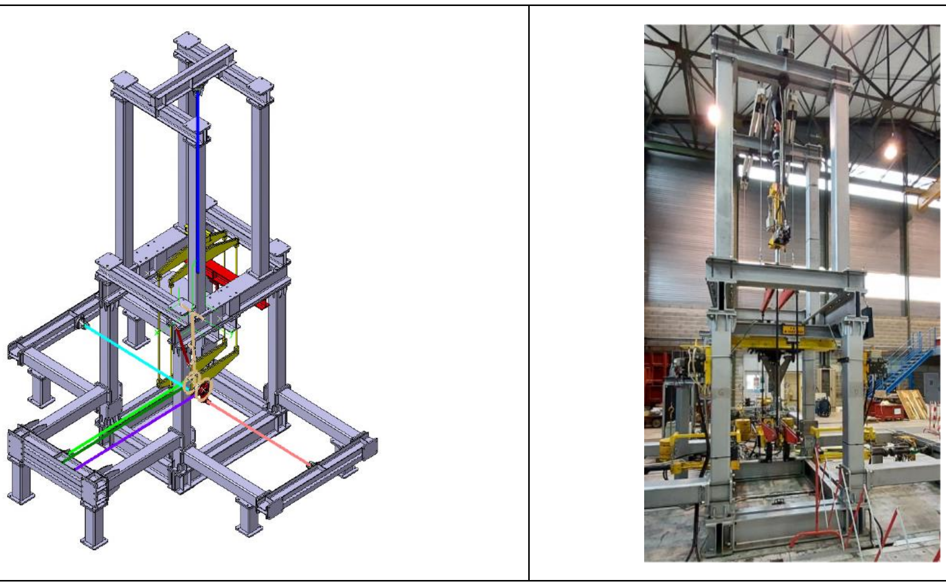


Figure 2: Test rig for the M2000 nose landing gear

Both test specimens are M2000 landing gears taken from the fleet in service. DGA TA has in charge the tools allowing the application of forces on the gear (false wheels with bearings according to the actual assembly of the wheel) and the interface pieces between the landing gear and the airplane.

Displacement sensors will be used to check the different loading paths of the test rig as well as programming fatigue spectrum load cases. The direction of movement measured by the displacement sensors will ensure that the forces on the landing gears are applied correctly.

The ground taxi, take-off and landing phases, as well as pressure cycling are taken into account to support the loading spectrum.

Several levels of control (NDT, dimensional controls and clearances) are performed to assess the behaviour of the landing gears throughout the test phase as well as before and after tests.

2.5. Description of composite mini-panel fatigue tests – arches project - LATECOERE AND DGA TA

P.Gail (Latécoère), Y.Ould Hammou (DGA TA)

The objective of this project is to verify the ability of a door to pass the certification tests using a quasi-equivalent structure and mechanical loading equivalent to a uniform pressure representing the cabin pressure.

In order to reach this goal, static and fatigue tests are performed on a mini-panel representative of a door, made of PEKK material by fiber placement, stamping and welding by induction. The mini-panel tests are bending tests.

The used methodology is composed of five steps:

Impact BVID* ➡ Fatigue BVID ➡ Limit load ➡ Ultimate Load ➡ Failure

* Barely Visible Impact Damage = damage in a composite material (for example CFRP) caused by a low-velocity impact from objects during maintenance or operation. Such objects can be dropped tools or runway debris.

BVIDs correspond to indentations whose depth, measured after relaxation, is of the order of the millimeter.

These indentations are made by impacting a hemispherical tool of 25.4 mm diameter and they aimed at generating a certain level of indentation depth, before relaxation (less than 60 minutes after impact), in order to obtain a lower indentation depth after relaxation (7 days). The assessment of the energy level required for these impacts were carried out during the pull-off, compression beam and flexion beam tests.

The depth of the desired indentations is associated with a level of detectability by detailed visual inspection (DVI).

The mini panel is composed of 3 distinct elements: skin, omega beam and Z frame. The skin/beam and skin/frame are thermomechanically assembled.

The loading principle simulates as best as possible the loading of the different parts of the panel under uniform pressure.

Loading is made up of point forces distributed throughout the panel and applied by hoist systems whose loading points are calculated by weighting the centres of gravity of the surfaces (Figure 1).

Figure 1: Presentation of the test rig

The mini panel was instrumented with strain gauges, displacement sensors and stress cell. In addition, tests are filmed using conventional cameras (up to 60 images per second) and fast cameras (up to 1000 images per second).

Visual inspections and NDT (Ultra Sound) inspections are carried out regularly during the various tests by DGA TA.

2.6. Description of fatigue tests for narang aerial refueling pod - SAFRAN AEROSYSTEM AND DGA

FX Fraisse (Safran Aerosystem), Y. Ould Hammou (DGA TA)

The objective of this fatigue test is to realize the qualification, for quasi-static fatigue loading, of the New Generation Aerial Refueling Pod (NARANG stands for NAcelle de RAvitaillement Nouvelle Generation) which equips the French Navy’s RAFALE fighter aircraft. A photography of the aerial refueling pod NARANG is presented in the Figure 1 below:

Figure 1: NARANG aerial refueling pod

For that purpose, the test has to validate the fatigue life of the structure with a safety factor. Below in Figure 2, is a part of the nacelle in its test facility:

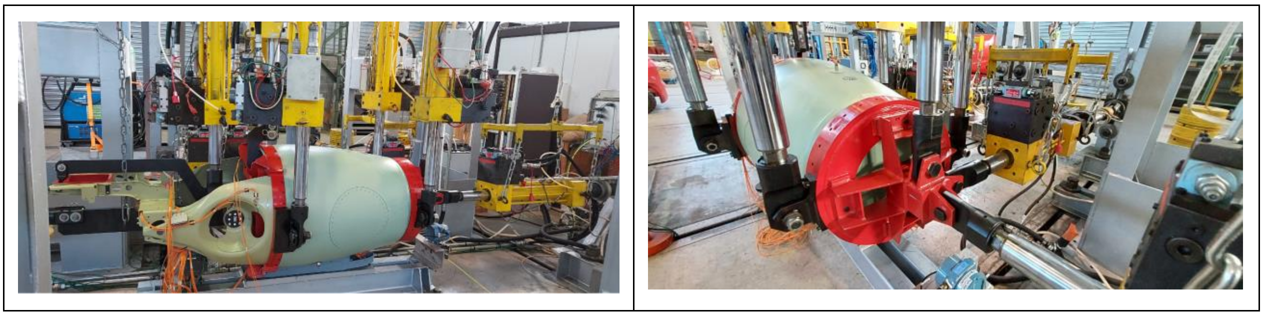


Figure 2: fatigue test facility for the NARANG pod

Quasi-static fatigue loading is introduced using 12 hydraulic jacks. The Figure 3 below shows the position of the hydraulic jacks:

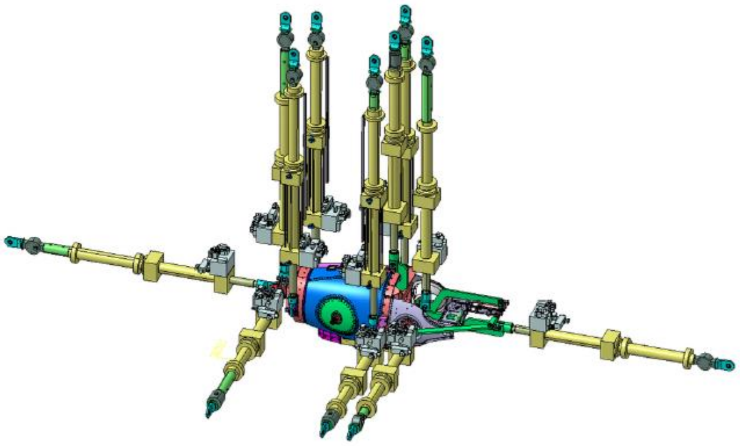


Figure 3: Hydraulic jacks set up

Moreover, as shown in the Figure 4 below, four pressure measurement stitches and one inflation tip are used to ensure the fuel pressurization of the nacelle during the test.

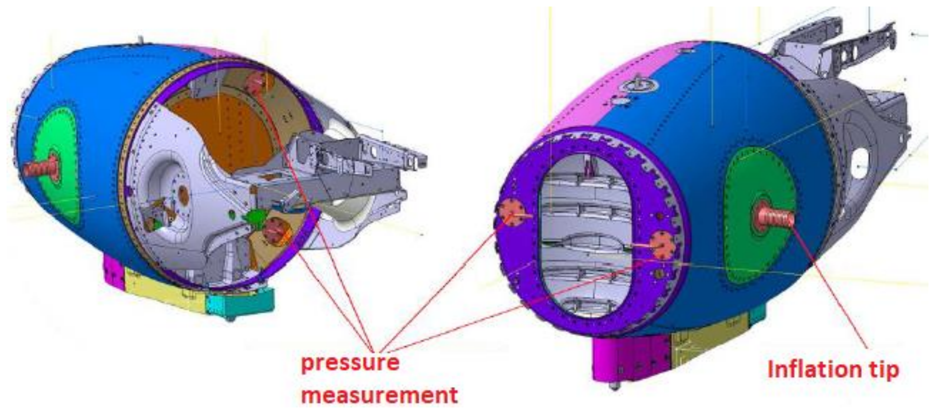


Figure 4: pressure measurement stitches and one inflation tip position

The nacelle is equipped with strain gauges and displacement sensors and NDT checks are carried out at regular intervals during the test to detect any damage.

3. FATIGUE CRACK GROWTH AND LIFE PREDICTION METHODS

3.1. Review of aeronautical fatigue investigations in France for Airbus Operations S.A.S: Fatigue crack growth and life prediction methods

Geoffrey Veragen, Jérôme Rousset

3.1.1. Introduction

On large scale simulation side, the numerical framework prototyped in Airframe R&T has been handover for future aircraft development.

The effort is now focused on assessing local fatigue initiation cracks prediction based on local volume meshed finite element model. The approach chosen by Airframe R&T is based on Continuum Damage Mechanics (CDM).

The main objective is to encompassed all the phenomena which impacted macro fatigue crack initiation in detail simulations.

The framework is investigated with the collaboration of ONERA. Continuum Damage Mechanics investigation.

3.1.2. Theory

Lemaitre and Chaboche (ONERA's model) have proposed the following nonlinear fatigue damage law, for uniaxial stress state:

$$dD = \left[1 - (1 - D)^{\beta+1}\right]^{\propto} . \left(\frac{\sigma_{max} - \bar{\sigma}}{(1 - D).M(\bar{\sigma})}\right)^{\beta} . dN$$

$$\propto = 1 - a\frac{\langle \sigma_a - \sigma_l(\bar{\sigma}) \rangle}{\langle \sigma_u - \sigma_{max} \rangle}$$

Chaudonneret extended Lemaitre and Chaboche's model to three-dimensional loading conditions. This model is used as a starting point for investigation.

The stress gradient effect is estimated with a volume average on the Damage value, according to an exponential weighting law.

At location x, the mean damage D(x) can be calculated with:

$$D_{(x)} = \frac{1}{\Omega_{(x)}} . \int_{V} \phi_{(x-\xi)} . D_{(\xi)} . d\xi$$

$$\phi_{(d)} = exp\left(-\left(\frac{d}{d_0}\right)^2\right)$$

The scale effect will be described with a statistical approach proposed by ONERA, considering a Weibull distribution and the weakest link theory.

3.1.3. Numerical implementation

The numerical approach is developed at coupon level to evaluate all the parameters and numerical framework. (Figure 1).

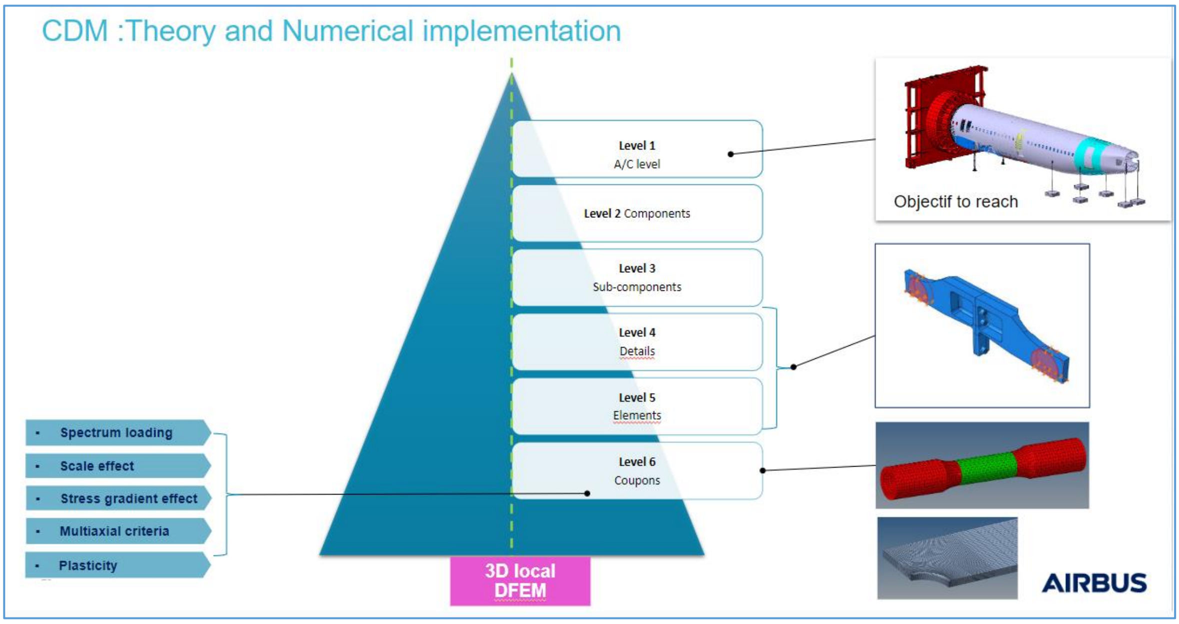


Figure 1: Pyramid used to consolidate the numerical framework

The challenge will be to bridge global analysis to local fatigue behavior in order to apply CDM at upper level of the pyramid. (Figure 2) It implies to define a process to manage all the global loading from global finite element to local detailed finite element model.

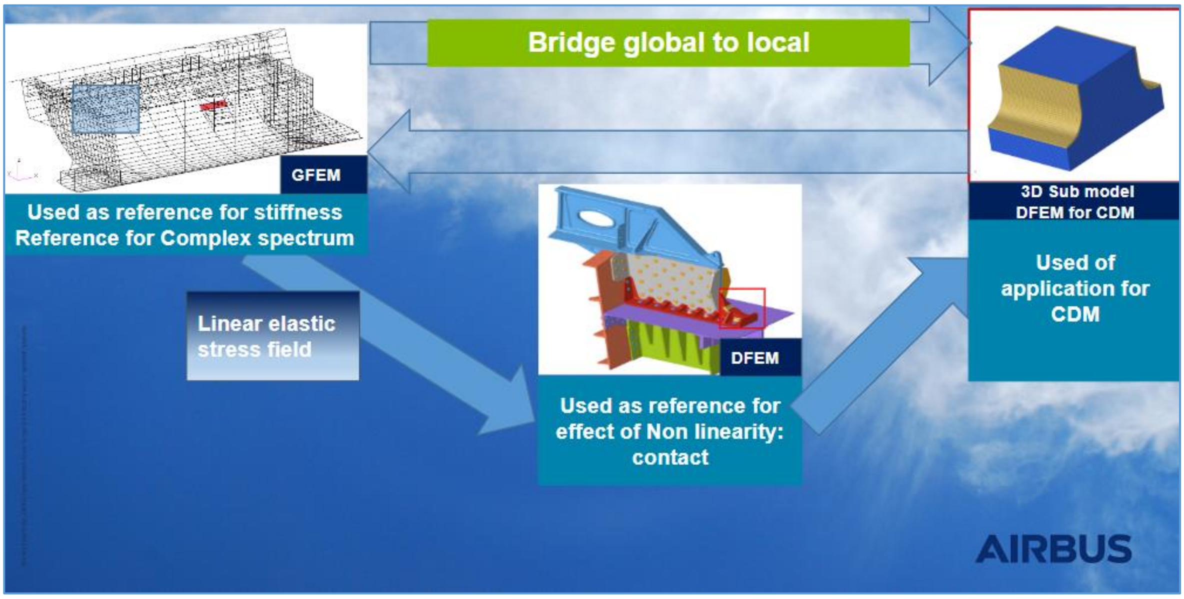


Figure 2: Challenge: create a bridge form global finite element model to local finite element model.

3.2. Damage tolerance of a hybrid lower wing panel - CONSTELLIUM

E. Nizery, J.C. Ehrström, M. Bellavoine, N. Bayona-Carrillo

For the next generation of single aisle aircraft, aluminum wing structures are well positioned: end-of-life recycling is strongly in favor of aluminum, and the lightweighting potential is comparable to the values claimed by competitor materials for similar applications or systems. The technical and cost competitiveness of the aluminum solution relies on advanced joining techniques and improved alloys with enhanced properties.

On the material side, the lower wing skins are particularly important for the overall wing performance, since they account for the largest weight share. Damage tolerance is a main design driver for lower wing skins, so any alloy improvement in crack propagation resistance can convert into weight savings or increased inspection intervals.

AW236, the new lower wing Al-Cu-Li Airware® solution is a key enabler of the next generation metallic wing. It has been developed to TRL6 with multiple industrial fabrications, with the following key characteristics (Figure 1):

- Reduction of density by 5% versus 2024 or 2027
- Improvement of fatigue crack growth resistance under a wing spectrum loading, with an improvement of life by 35% versus 2027 T3 or 62% versus 2024 T3.

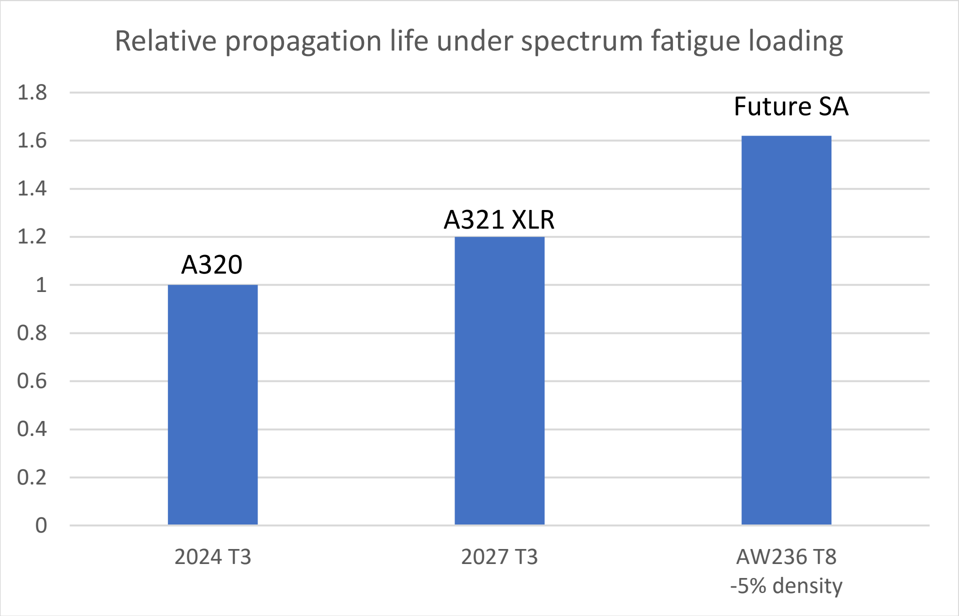


Figure 1: Key characteristic of the new Al-Cu-Li alloy, AW236 T8

4. REPAIRS AND STRUCTURAL INTEGRITY OF COMPOSITE LAMINATES

4.1. Development of a numerical model of tire fragments for high-speed impact – DGA TA

J-R.Augustin

4.1.1. Introduction

The study carried out within the consortium, in the TIOC WING Cleansky 2 European funded program, has three objectives:

- Create a composite wing to contribute to reduction in aircraft weight.
- Analyze the effect of a tires debris impact on a composite panel.
- Optimize the design and test phases by improving our numerical simulation expertise.

4.1.2. Test measurements

Twelve tire impact tests have been performed on a rigid frame equipped with load sensors and accelerometers, according to arrangement of the TIOC WING Cleansky 2 project (figure 1). The aim of these dynamic tests campaign is to analyze the behavior of a small tire fragment for its characterization, in order to develop a numerical model.

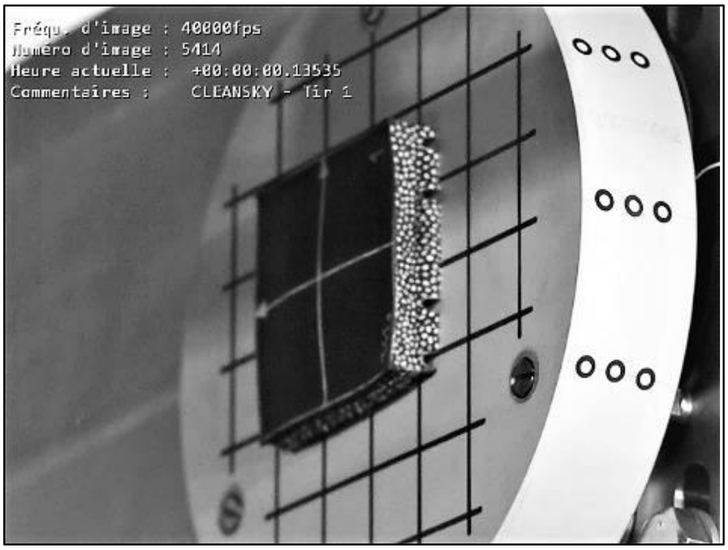


Figure 1: Tire impact picture

A 3D DIC stereo correlation measurement was carried out on the edge of the tire to measure its strain and the strain rate (Figure 2).

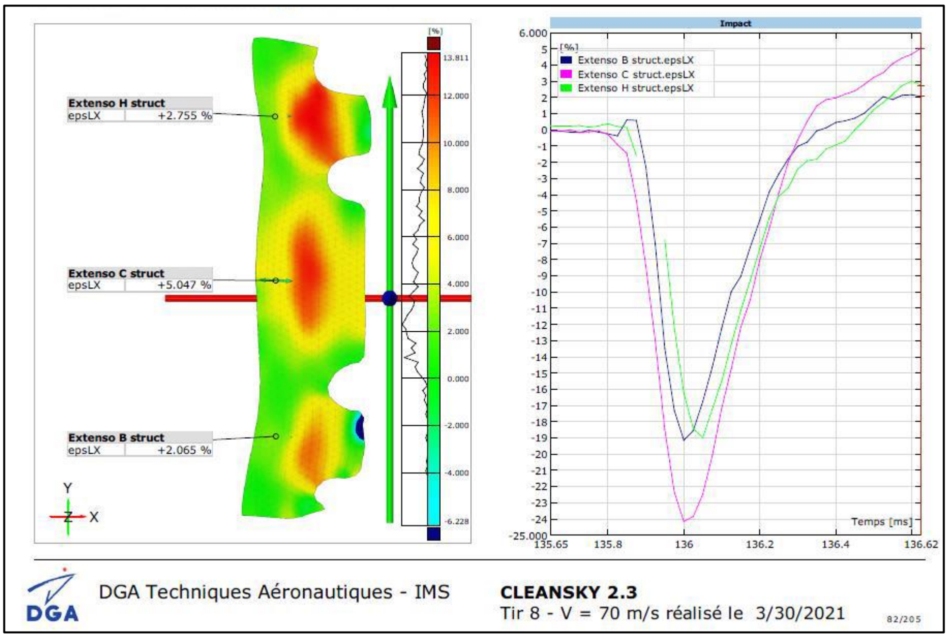


Figure 2: 3D DIC measurement

4.1.3. Numerical geometrical analysis

The development of a complex model being time-consuming and expensive, a study has been set up to study the feasibility of simplifying the geometry of the numerical fragment (Figure 3).

The parameters studied are the influence of the presence of the reinforcement, the curvatures of the fragment and the presence of grooves. The conclusions of this study are:

- modelling of the reinforcement is necessary,
- impact surface is dimensioning and therefore the simulation must take into account the grooves,
- small influence of curvatures.

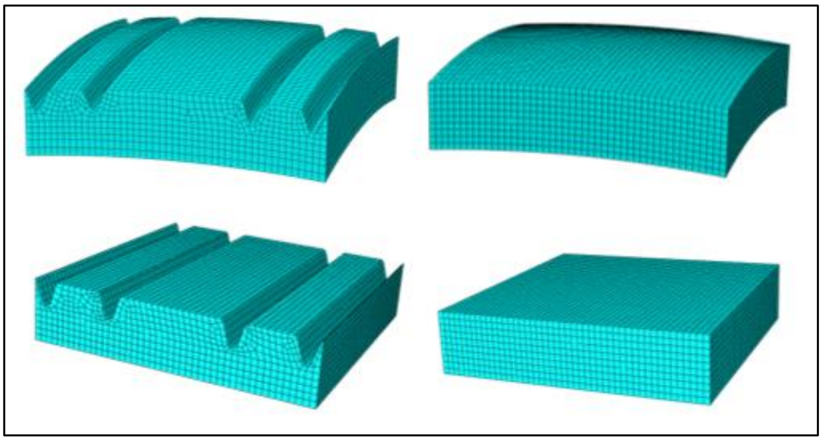


Figure 3: tire debris models tested

4.1.4. Tire behaviour model

There are many hyper elastic model to model the behaviour of rubber. The simplest is the Neo Hook model (elastic behaviour, 1 parameter) and the most complex used for this study is the second order Ogden model (6 parameters).

Ogden law :

$$W = \sum_{i=1}^{N} \frac{2\mu_i}{{\alpha_i}^2} \times \left(\overline{\lambda_1}^{\alpha_i} + \overline{\lambda_2}^{\alpha_i} + \overline{\lambda_3}^{\alpha_i} - 3\right) + \sum_{i=1}^{N} \frac{1}{D_i}(J^{el} - 1)^{2i}$$

with μ_i, α_i, D_i material parameters and N the order of the model

The bibliography has shown that the OGDEN model was mainly used in the tire fragment impact study. To compare the different models obtained, the maximum load obtained during the tests was used (Figure 4).

The reference for the comparisons is the most complex model obtained called the "optimal model". The results make it possible to conclude that for the case study the Neo-Hook model makes it possible to obtain reliable results. This result can only be applied for cases of flat impacts.

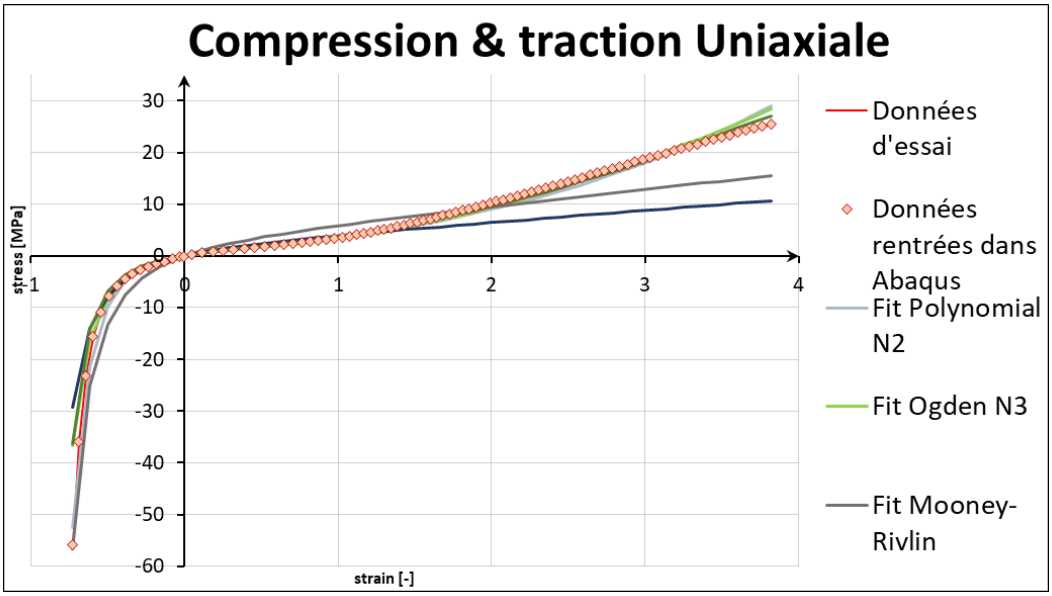


Figure 4 – Comparison of the material law for the tire debris

4.1.5. Conclusion

Throughout the project, an in-depth analysis was made of the behaviour of a pneumatic fragment on impact. The complex model made it possible to establish and conclude on the important parameters to be taken into account for the modelling of a tire impact on a composite panel:

- Not taking into account the Mullins effect is conservative if only new tires are used,
- up to 100 m/s the viscoelasticity has no influence, for higher speeds it could have a strong impact.
- a hyperelastic model of the Neo Hook type allows a good representativeness of the tests,
- bends have no influence on the results,
- Impact surface (grooves) have strong influence on the results. Construction of an equivalent surface makes it possible to eliminate the grooves.

All these results were obtained for a flat tire impact for a small debris, configurations considered to be the most significant. Particular attention must be paid to the conditions of use of the tire during the test to best adapt the model.

4.2. Simplified modelling approach of composite bonded stepped repairs – DGA TA / ICA

JB. Orsatelli[1,2], E. Paroissien[2], F. Lachaud[2] et S. Schwartz[2]
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4.2.1. Introduction

Composite bonded flush repairs offer many advantage over conventional mechanically fastened repairs. They can be performed with either a scarf or stepped shape, allowing to achieve high strength recovery of damaged structure without drilling or adding bolts.

However, there is no current standard method to design joints. Numerous academic studies proved that finite-element (FE) modelling, or more simple semi-analytical models, are suitable to design stepped repair design, but the question of knowing whether a simplified 2D stepped joint model can be representative for the behaviour of 3D stepped repair (figure 1) is still open in the literature.

Hence, this work aims to compare several levels of modelling of a stepped repair to assess the influence of modelling hypotheses on the predicted strength of a stepped repair.

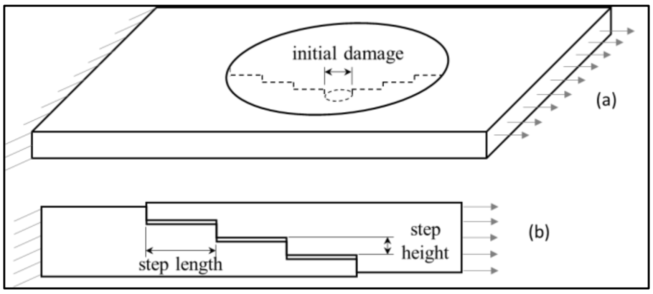


Figure 1: Stepped repair (a) and its equivalent stepped joint (b)

4.2.2. Material and methods

Two main levels of modelling were considered: 3D stepped repair and its 2D equivalent stepped joint (figure 1), which is the section of the 3D model aligned with the direction of the load.

The 3D stepped repair was modelled by FE, and five different stepped joint model were tested as simplified approaches: (i) 1D macro-element (ME) bar ; (ii) 1D ME beam ; (iii) 2D FE plane strain; (iv) 2D FE generalized plane strain ; (v) 3D FE stepped joint (Figure 2).

ME modelling[1] is a resolution scheme associated to a simplified modelling of a bonded overlap, with bar or beam behaviour of the adherends on an elastic foundation. It handles nonlinear behaviour of the adhesive layer in the same as FE cohesive zone modelling does.

All models used the same geometrical and material parameters. Bonded interfaces were modelled using cohesive zone modelling. A large range of adhesive fracture toughness and step length were tested to explore the field of validity of each model.

All models account for shear and peel effects in the bonded joints, expect for the 1D bar models that does not account for peel effects. Loading was applied in form of uniaxial tension, with edges fully clamped.

4.2.3. Results and discussion

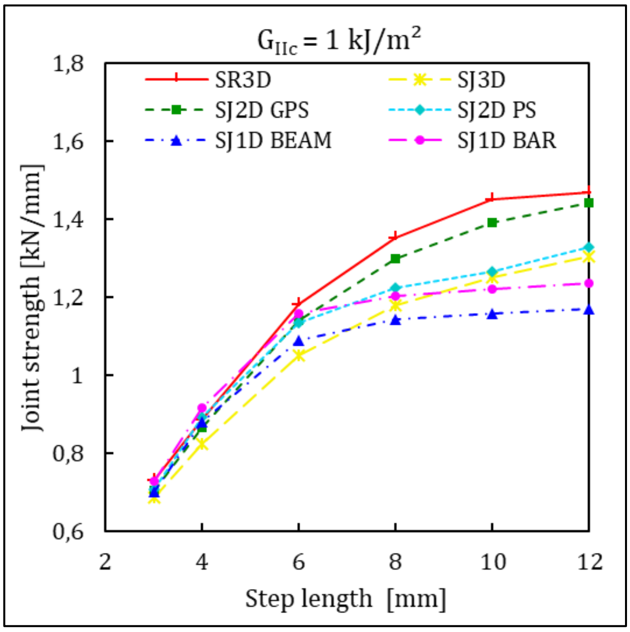


Figure 2: Comparison of predicted strength FE and ME models

First, a stress analysis highlighted that there is very little deviation between the bondline stress in FE models. It confirmed that the stress state in the most loaded area is close to the one in the equivalent stepped joint. However, ME models tended to underestimate bondline shear stress compared to FE.

The results of the presented models were compared in term of predicted load-carrying capacity of the bonded joint (Figure 2). Because this study does not address the failure of the composite adherends, the predicted joint strengths may be higher than the typical strength of a carbon/epoxy laminate. The sensitivity analysis showed as expected than the strength of the joint increases when the step length or adhesive fracture toughness increases.

Among FE models, the trend of the deviation between the four different models remained the same no matter the adhesive fracture toughness and step length. One the one hand, the FE 3D stepped repair model was the one with the highest predicted strength.

This is reasonable as the circular patch allows load bypass around the most loaded area of the repair. On the other hand, FE 3D stepped joint model was the FEM model with lowest predicted strength.

This is related to edges effects, leading to anticipated failure of the joint in this model. The FE 2D plane strain model lied between FE 3D stepped joint and FE 2D generalized plane strain. Finally, the SJ2D GPS model was the closest to the SR3D in any case.

ME models were conservative compared to FE models. It was quite surprising as the tended to underestimate shear stress compared to the latter, but it could be explained by the fact that they neglect shear deformations of the adherends, which tend to increase failure load of the bonded joint when it is taken in account.

4.2.4. Conclusions

All simplified models were conservative compared to 3D FE stepped repair. The use of a 2D FE generalized plane strain model seems to be the best simplified model of a stepped repair: it was in agreement with the full 3D model in terms of failure scenario, had less than 3% average absolute deviation compared to the latter, and saved significant computing time.

Macro-element modelling of the equivalent stepped joint was unexpectedly conservative most of the time compared to FEM models, expect in the case of short steps or fragile adhesive.

5. NDI, INSPECTIONS AND MAINTENANCE

5.1. A new approach to accidental damage on aircraft metallic structure – AIRBUS S.A.S / AIRBUS Limited

Sébastien Amiable[1], Ben Ogborne[2] and Alain Santgerma[1]
[1] AIRBUS Operations SAS, France
[2] AIRBUS Operations Limited, UK

NB: Although much of this study was carried out in France, this new approach is the result of multi-national work.

5.1.1. Introduction

Commercial aircraft are exposed to the risk of accidental damages during production, service exploitation, and maintenance. Accidental Damage is characterized by the occurrence of a random discrete event which may reduce, immediately or after a period of time, the inherent level of residual strength of the structure.

5.1.2. Approach previously applied to define inspection requirements

The areas susceptible to Accidental Damage are identified using service experience, following an ATA MSG-3 (Air Transport Association Maintenance Steering Group) analysis procedure. MSG-3 is a decision-logic procedure for determining scheduled maintenance requirements in the frame of the MRB (Maintenance Review Board) process.

5.1.3. Rationale for a new approach

From the very first A300, AIRBUS defined and applied a conservative approach to define the inspection requirements for Accidental Damage. The experience accumulated in tests and service usage may now be used to define an approach which is more realistic, in line with the physics.

It is likely that the accidental damages having the potential to interact with fatigue would be detectable by visual means, under scheduled maintenance. Hence, it is more effective to look for accidental damage, instead of hypothetical fatigue cracks that may initiate and grow as a consequence of an accidental damage.

5.1.4. New accidental damage approach

5.1.4.1. Concept idea

The inspection requirements for accidental damage are defined in a more realistic way when the Fatigue and Damage Tolerance analysis results are combined with the Maintenance Engineering data.

The inspections are primarily aimed at finding accidental damages, before any interaction with fatigue could occur. The various damage categories defined in EASA AMC 20-29 (Composite Aircraft Structure) were used in Figure 1 to illustrate the domain of application of the scheduled inspections for accidental damage.

A Stress Sensitivity Rating is introduced. It is intended to rate the likelihood of an accidental damage to reduce the structural strength capability and to interact with fatigue damage.

The repeat inspection interval, expressed in calendar time, is now determined with a double entry table combining the damage frequency rating with the Stress Sensitivity Rating.

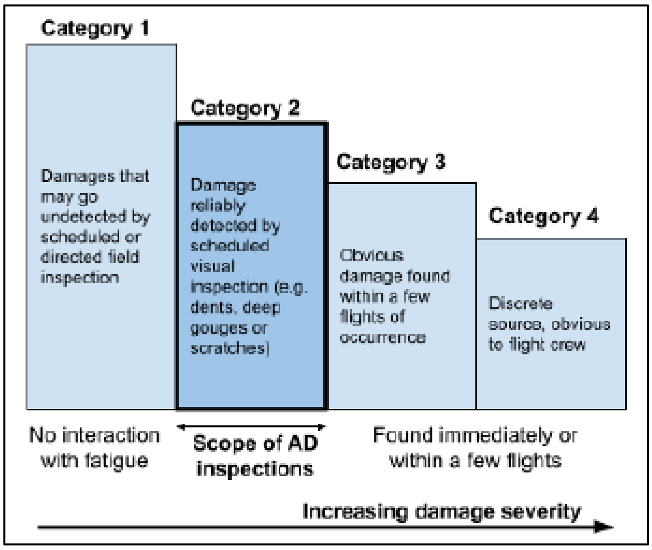


Figure 1: Scope of scheduled inspections for Accidental Damage (AD).

5.1.4.2. In-service experience

In service experience shows that only one case (severe impact during cargo loading on A320) was a true case of fatigue crack caused by accidental damage (Figure 2).

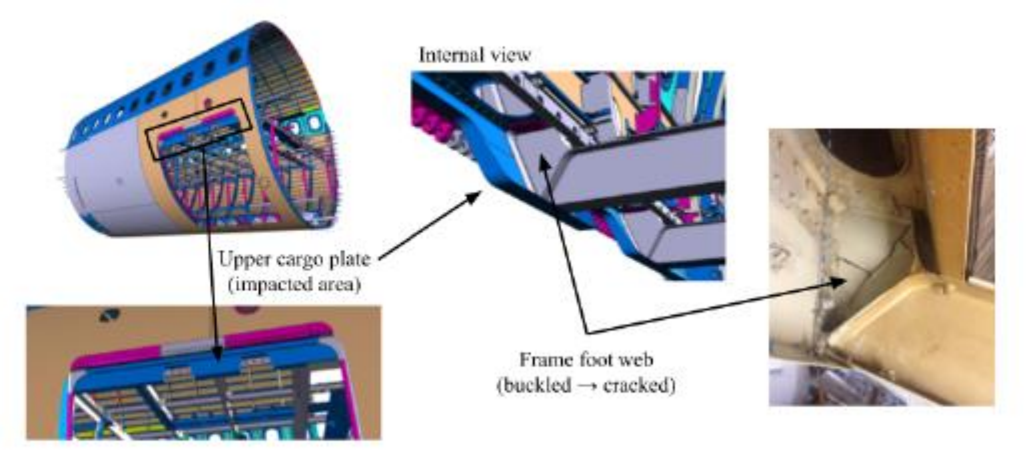


Figure 2: Case of interaction between accidental damage and fatigue.

This survey demonstrated that accidental damages are found well before significant interaction with fatigue damage occurs.

5.1.4.3. Test experience

Full-Scale fatigue tests provide an opportunity to assess the structural behavior in the presence of typical repairs, allowable damages, and other defects. As an example, more than 100 dent damages of different severities were intentionally applied on A380 and A320 Full-Scale Fatigue in the 2000s

In the context of this new accidental damage approach, it was interesting to determine the dent depth from which interaction with fatigue may occur, and to compare this with the detectable depth (Figure 3).

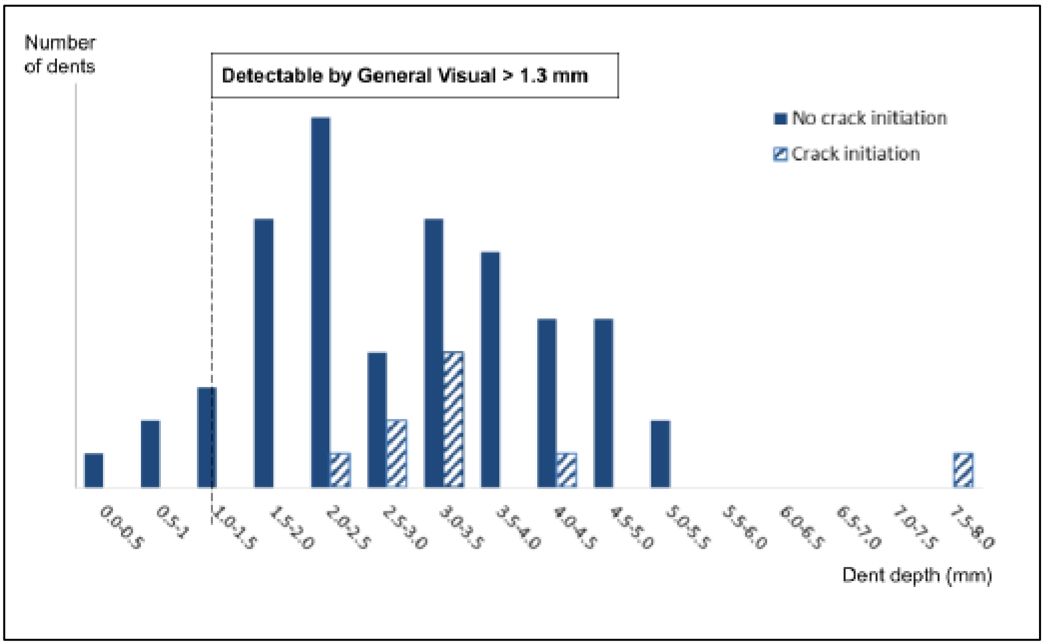


Figure 3: Test results with dents.

Fatigue cracks initiated on some of the deepest dents (Figure 4). However, it took more than one Design Service Goal before the first cracks were detected during the test.

Figure 4: Fatigue cracking from deep fuselage dent.

Accordingly, it confirmed that the initial approach purely based on Damage Tolerance analysis was overly conservative.

5.1.4.4. The new approach in details

The Accidental Damage analysis is done by means of an assessment based on a rating system, consistent with the ATA MSG-3 philosophy. The following criteria are considered for each Structural Significant Item (Figure 5).

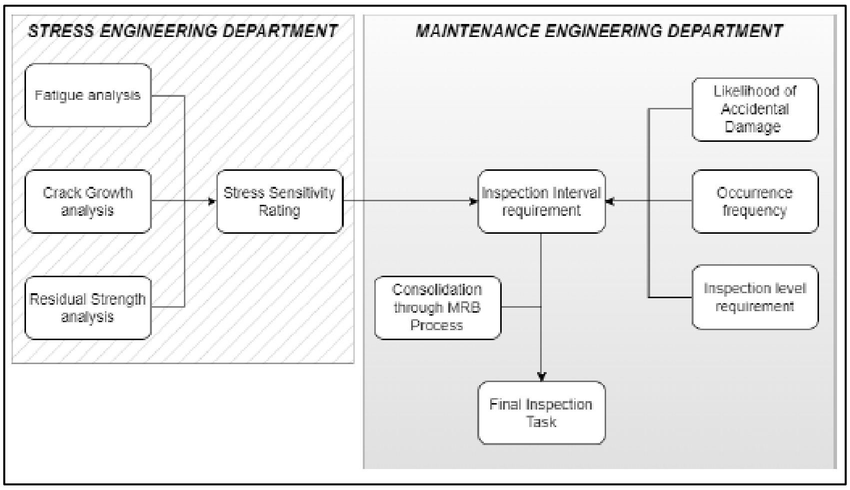
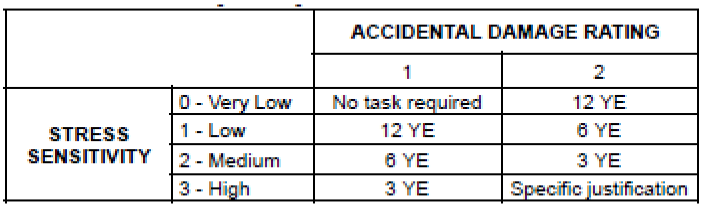


Figure 5: Overview of the new approach.

- Likelihood of the Accidental Damage sources
- Occurrence frequency of Accidental Damages
- Stress Sensitivity Rating (Interaction with fatigue damage)
- Inspection level determination
- Repeat Inspection interval (Table 1)
- Final inspection requirement



		ACCIDENTAL DAMAGE RATING	
		1	2
STRESS SENSITIVITY	0 - Very Low	No task required	12 YE
	1 - Low	12 YE	6 YE
	2 - Medium	6 YE	3 YE
	3 - High	3 YE	Specific justification

Table 1: Repeat Inspection interval determination.

5.1.4.5. Application of the new approach

Once defined, the new approach was reviewed and agreed with all stakeholders.

Implementation of this new approach on the various AIRBUS products started in 2019, with very good feedback from the operators.

5.1.5. Conclusion

The collective experience from operators, maintenance & repair organizations, AIRBUS maintenance engineering and stress specialists was combined to build a new approach to define the scheduled inspection tasks for accidental damage.

The AIRBUS test and service experience demonstrated that the accidental damages susceptible to interact with fatigue damage are relatively obvious and detected well before any interaction occurs.

The new approach is less conservative, in line with the physics of the phenomenon. It combines an MSG-3 based procedure together with fatigue and damage tolerance analysis results.

The consolidation with the environmental and zonal inspection requirements avoids a duplication of inspection tasks. Overall, the effectiveness of the inspection program for accidental damage was improved and the new approach has been recognized as a “huge improvement in scheduled maintenance” by the A350 maintenance working group operators.

5.2. Automated UAVs for aircraft dent inspections - DONECLE

R.Tanquerel, M.Calybrough and A.Poisson

Improving aircraft life extension and life management support is crucial for any aircraft operator. For safety reasons, every aircraft undergoes many maintenance operations and pre-flight checks during its lifetime. The strict damage tolerances require frequent visual inspections to ensure the integrity of the aircraft and maintain the aerodynamics.

Most of the time, carried out manually, operators require heavy equipment, such as mobile elevating platforms, scaffolding, and lifelines, to access all areas of the aircraft's external surface. Those operations are dangerous for the workers and can damage the aircraft while inspecting it. Moreover, it's time-consuming because all damages must be detected, measured, localized, and reported.

During visual inspections, the inspector and his team must perform various job cards to identify structural defects: corrosion, erosion, lightning strike, paint defect, crack, markings, dents, bumps, etc. Inspecting dents and bumps is one of the most challenging manual tasks (Figure 1).

This assessment is typically carried out during regulatory checks and after severe weather events such as hailstorms or accidental contact with ground support equipment.

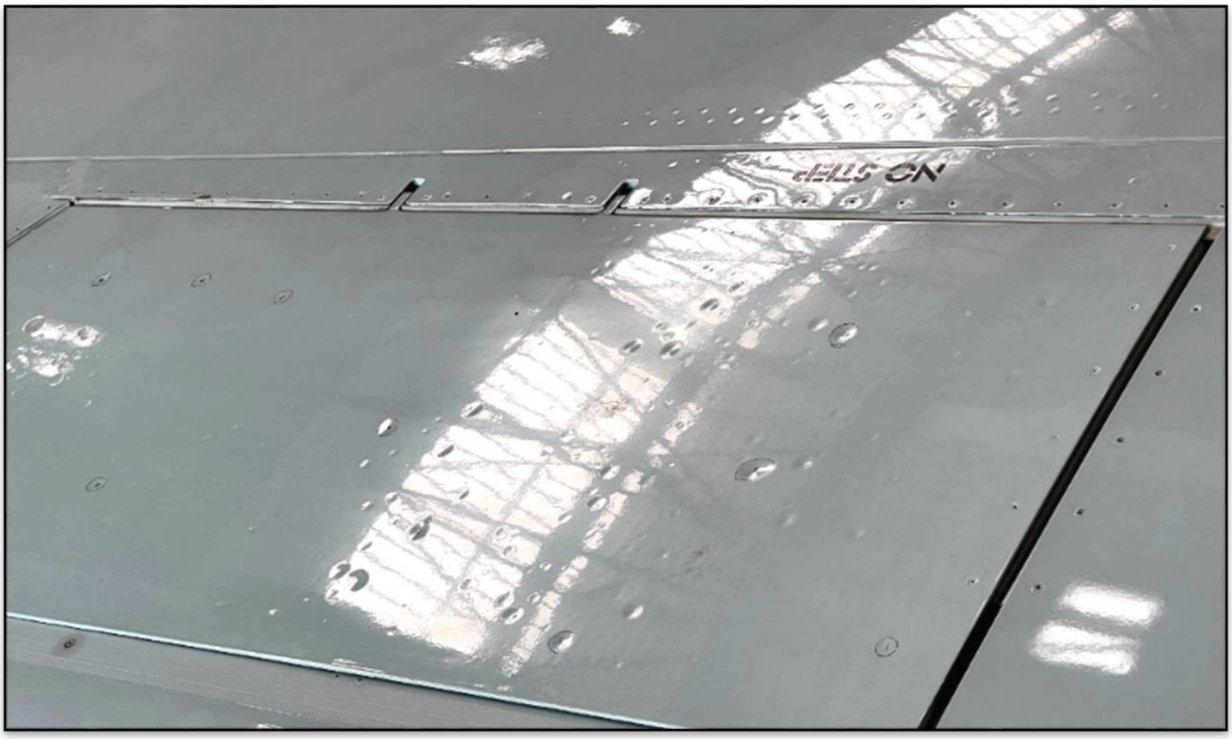


Figure 1: Hail damage on an aircraft wing

The detection of dents and bumps on aircraft is carried out by qualified inspectors using either manual tools or automatic aids. Without automatic aids, dent detection relies on the inspector's eyes, and the measurement comes from a depth gauge. By measuring the depth and diameter of a dent, we can calculate the critical ratio that helps us determine if the dent requires repairs. If it does, the aircraft will have to be grounded until the repairs are completed.

Ensuring the accuracy of these measurements is crucial, as the effectiveness of depth gauges heavily relies on the operator's appreciation. There have been noticeable variations in measurements, even among skilled inspectors. With automatic aids, these disparities are reduced.

However, in both cases, an inspector needs to have access to the surface, and while the use of handheld tools is faster than manual methods, both methods are very time-consuming. For example, a hail impact inspection can take up to 8h/m^2 with manual inspection and 1h/m^2 with handheld tools.

To improve the overall maintenance cycle and increase safety, the French company Donecle, create in 2015, has developed automated UAVs for inspections in the aeronautic field. The solution aims to provide standardized, faster, and precise aircraft and component inspections. In 2022, the company released a new drone family named Iris, composed of two quadrotor platforms, Iris GVI for general visual inspection and Iris dentCHECK for dent and bumps detection and measurement.

The Iris dentCHECK UAV (Figure 2) results from a collaboration between Donecle and the German company 8tree. Those two companies have joined their expertise and capabilities to offer a solution outside the box. This innovation combines Donecle's automated drone and 8tree's dentCHECK® 3D sensor. This unique technology can detect and measure dents and buckles on the aircraft's surface 50 times faster than manual methods.

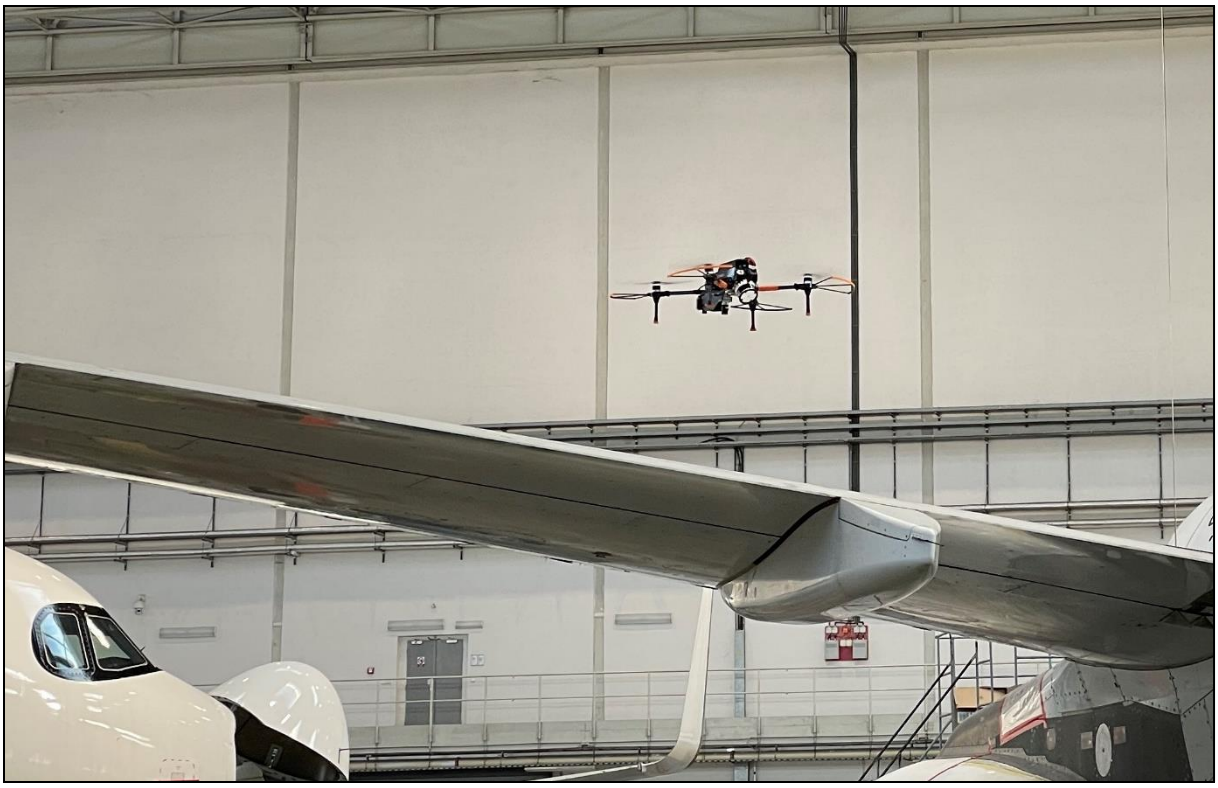


Figure 2: Iris dentCHECK during an inspection

This drone flight is completely automated, with no remote control or backup pilot required. Each inspection captures hundreds of high-definition images transferred to a tablet for analysis.

The analysis is automated with advanced artificial intelligence algorithms based on machine learning that assist the operator throughout the whole inspection process directly from a dedicated computer. Then, the software can automatically generate reports and store all the data in a secured cloud to provide aircraft digital history and inspection tracking.

The UAV flies thanks to a laser positioning technology that enables safe, automatic flight with millimetric accuracy and centimetric positioning. Navigation sensors ensure safe operation by preventing collisions (Figure 3).

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. Iris dentCHECK can inspect up to 2 square meters per minute, leading to a wing inspection time of about 30 minutes for an A320 or a B737. During its autonomous flight, the Iris dentCHECK sensor detects and measures dents down to 0.1mm depth accuracy.

Figure 3: Iris dentCHECK inspection on Rafale Fighter aircraft

The drone's onboard 3D sensor uses the same software behind 8tree's dentCHECK® handheld scanner. 8tree's dentCHECK tool is approved and recognized by all major aerospace OEMs such as Airbus, Boeing, etc. 8tree claims its tool is more consistent, precise, and faster than traditional methods.

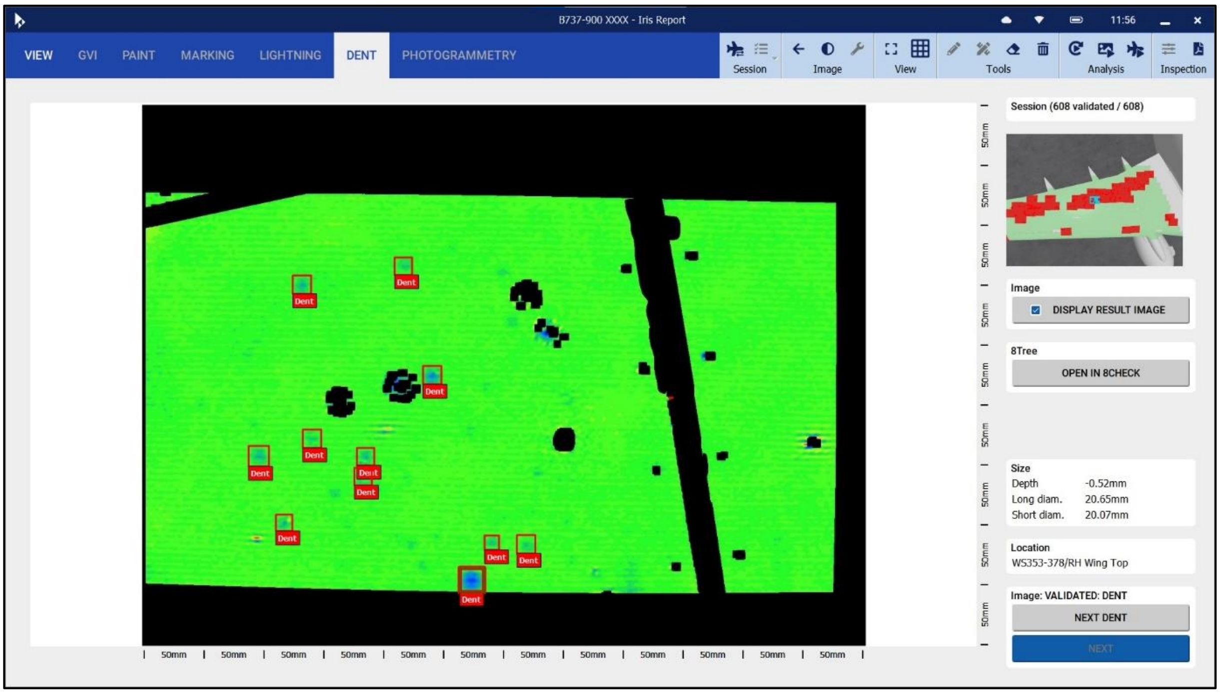
The technology used for measurement is structured light. Structured light 3D scanners are designed with a sensor that includes a projector and one camera placed strategically around the projector.

The scanner projects patterns of light on the subject, here the aircraft's external surface, to looks at the deformation of the pattern with the cameras. By understanding the cameras' location in relation to the projector, we triangulate the position of every point captured by both devices simultaneously.

The process of integrating a structured light sensor differed significantly from integrating a regular camera and flash combination. To address the ambient luminosity variations, we developed an algorithm that automatically calculates the best luminosity and exposure for the camera and the projector.

To ensure minimal displacement between the projections of the different patterns, we used control laws derived from those we use for outdoor flight for Iris GVI.

To further speed up the process and help the human inspectors, the company has integrated tools to detect, measure and display dents on a digital aircraft mock-up. The inspector can also select dent depth, diameter, and critical ratio thresholds to review only the most critical dents. After a review of the images, the user can generate a report compiling all the results in a single pdf file (Figure 4). The user can also upload the report and the photos to save them for the future.



Session (608 validated / 608)

Size
Depth -0.52mm
Long diam. 20.65mm
Short diam. 20.07mm

Location
WS353-378/RH Wing Top

Image: VALIDATED: DENT

Figure 4: Dent inspection with the Iris Report software

Our following projects involve the calculation of a digital mock-up of the aircraft. By combining all the scans, our technology should be able to calculate a digital twin of the aircraft. This will help assess the overall airframe integrity, increasing safety and repair planning efficiency. Last, the digital history will help further track repair areas and damage trends and improve our understanding of how airframes age.