**ICAF 2007 Conference – Royal Continental Hotel Napoli, Italy - 14-15 May 2007**

# REVIEW OF AERONAUTICAL FATIGUE INVESTIGATIONS IN FRANCE DURING THE PERIOD MAY 2005 - APRIL 2007

Compiled by
Jean ROUCHON
and
Thierry ANSART

Toulouse Aeronautical Test Center (CEAT)
31131 BALMA FRANCE

DIRECTION DES ESSAIS

CENTRE D'ESSAIS AERONAUTIQUE DE TOULOUSE

# INTRODUCTION AND ACKNOWLEDGMENT

The present review, prepared for the purpose of the 30th ICAF conference to be held in Napoli (Italy), on 14-15 June 2007, summarises works performed in France in the field of aeronautical fatigue, over the period May 2005-April 2007.
Topics are arranged from basic investigations up to in-service monitoring.
References, when available, are mentioned at the end of each topic.
Correspondents who helped to collect the information needed for this review in their own organisations are :

- Fabrice Congourdeau, Cyrille Schwob, Sébastien Didierjean, Laurent Chambon, Benoît Petitjean and Bertrand Journet for EADS Innovation Works
- Anne-Laure Lafly, Delphine Gardonio, Denis Campassens and Alain Santgerma for Airbus France
- Lionel Le Tellier for Dassault Aviation
- Nicolas Baréa and Gilles Garrigues for Latécoère
- Jean-Fred Bègue, Damien Théret and Jean-Philippe Torelli for CEAT.

They will be the right point of contact for any further information on the presented topics.
Many thanks to all of them for their contribution

# TABLE OF CONTENTS

# 6.1. FATIGUE LIFE PREDICTION STUDIES AND FRACTURE MECHANICS

## 6.1.1. Fracture criteria for residual strength analysis (Dassault-Aviation, DGA / SPAé and CEAT)

Within the framework of the French PEA n°022601 "Improvement of design and structural strength of combat airframes", a study has been conducted with the aim of improving the Dassault-Aviation residual strength calculation methodology for cracked structures. Based on our current practice, the R-curve concept often fails indeed to provide reliable predictions for the fracture of cracked structures.

A new approach has therefore been investigated, based on an equivalent crack size “aeq” concept with an assumed linear relationship between this geometric parameter and the fracture toughness, Kc = Kc(aeq). A number of fatigue tests on standard coupons and also on specimens with a more complex geometry, made from 2024 T3 and T351 material, have been performed and the resulting test data base has been used to identify the parameters of the former relationship so that the corresponding fracture criterion K(a) = Kc(aeq) can be fully determined.

*Figure 1 : visualization of stable crack growth within the material (dye application during loading to fracture)*

The diagram below where the fracture toughness values obtained for the equivalent crack length values computed for the test specimens under the fracture loads reached in the tests using the Kc(aeq) law introduced before (calculated Kc's) are compared with the stress intensity factor values K(a) computed for the crack lengths “a” reached under the failure loads ("measured" Kc's), exhibits a fair predictability of the criterion developed.

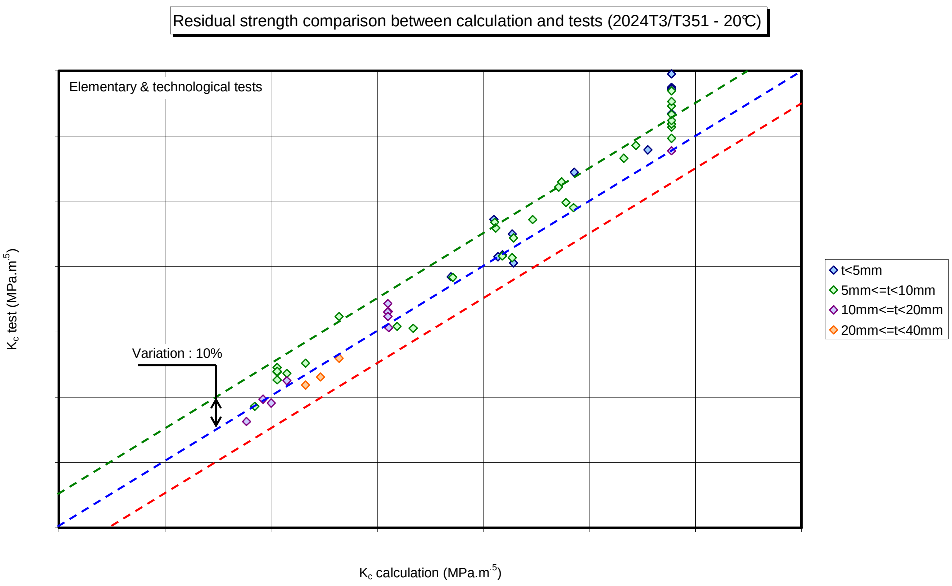



*Figure 2 : residual strength comparison between calculation and tests*

Since the previous study was concluded, criteria based on the same formulation have been developed for other materials; they are now extensively used for damage tolerance analyses of the critical structural parts of Dassault-Aviation aircraft.

Further investigations are nevertheless still necessary to apprehend the possible effects of various material and design parameters (e.g. sheet thickness) on the identified Kc(aeq) laws.

### 6.1.2. Thermal effects in F&DT assessment (Airbus France)

During each flight, the aircraft structure is submitted to important changes of temperatures. Structures of most recent aircraft models are made of hybrid materials, with different thermal expansion coefficients. Temperature induces, into such hybrid structure, thermal stresses that add up to the mechanical stresses. As structural areas sensitive to fatigue such as fastened joints are affected by these temperature changes, such thermal effects have to be taken into account in F&DT analyses. A significant work has been carried out to understand the consequences of these temperature changes on structural fatigue strength and to develop adequate methodology to account for them in F&DT analyses.

Two complementary effects have been identified, and need to be accounted for in the analysis: a global effect and a local effect.

The global thermal effect is a modification of load distribution in the structure, due to temperature variation in hybrid structures. It is typically the case of large composite parts embedded in metallic structures. The global thermal stresses are determined thanks to global FEM calculations, based on temperature mappings of the structure established at various phases of ground and flight. These stresses are superimposed to the mechanical stresses used for F&DT analyses.

The local thermal effect is limited to assemblies of different materials. Due to different thermal expansion coefficients, additional stresses may be induced locally between fasteners. These local thermal stresses may change load transferred, affect local stress concentration factors and in some cases may also change the most fatigue sensitive location. As temperature and mechanical stresses evolve independently during ground-air-ground cycle, the ratio between thermal stresses and mechanical stresses is not constant all along the mission.

Then, a refined calculation method for fatigue assessment of hybrid joints has been developed to account for these local thermal effects, based on the superposition of mechanical spectrum and temperature variations. Detailed calculations of the hybrid joint are performed at every ground and flight phase, taking into account actual mechanical load and temperatures of every phase.

Moreover, in order to investigate experimentally local thermal effect and to validate the developed method, a test program on aluminium alloys/CFRP coupons has been launched. The aim of this test program is to assess the impact on fatigue lives of a thermal cycling superimposed to a mechanical cycling, for several configurations (geometry, material, loading). Reference fatigue lives are generated under pure mechanical constant amplitude loading. The thermal tests are performed under combined thermal and mechanical cycling, temperature and mechanical stress evolving at the same time.

### 6.1.3. F&DT assessment of bush repairs (Airbus France)

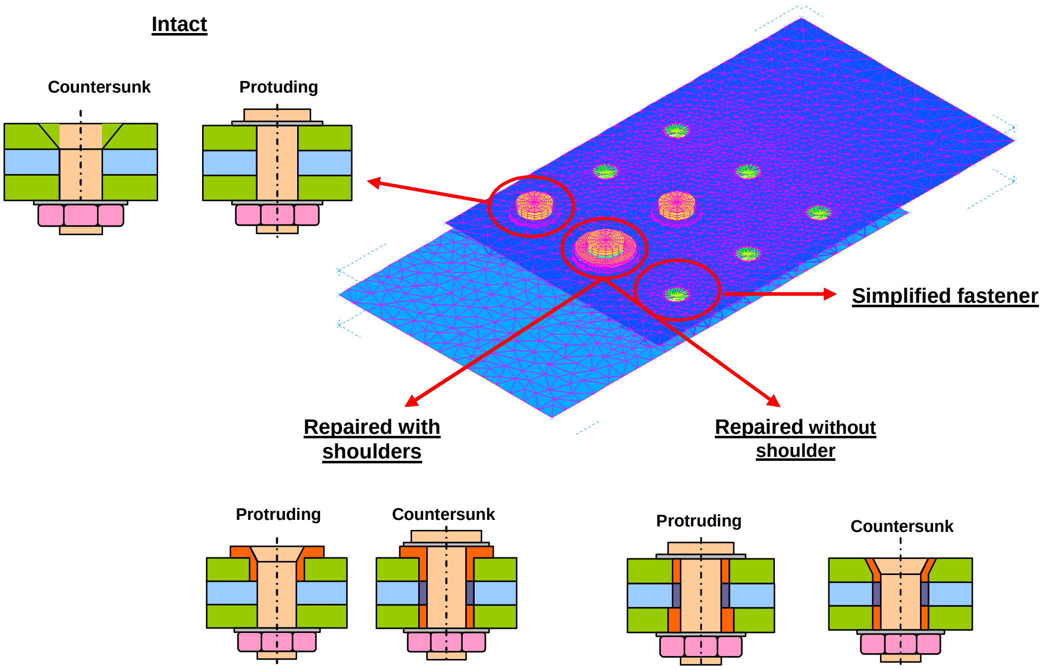
Local bush repairs are regularly installed in the context of production concessions and in-service operations. In order to provide quick and accurate responses in terms of engineering specifications and stress justification (mainly fatigue), a two years research program has been carried out, including theoretical and experimental investigations.

Fatigue tests have been performed on numerous configurations, including single and double shear joints, to assess the fatigue benefit of technological processes (interference fit, cold working, bushes…) in the presence of a very limited edge distance. The fatigue life improvements may be strongly reduced, negligible sometimes, particularly for the cold working processes (too strong deformation of all the edge ligament limiting the creation of local residual compression stresses).

In parallel, a generic FEM has been created. Various hole repair configurations, including oversize and/or bush (see figure) may be simulated at one or several holes. Variable parameters like hole repair configuration for every hole, holes position, dimensions are specified by the user. The aim of this study is to analyze, through experimental design, the mechanical behaviour in order to get:

- the relative influence of the numerous parameters involved in order to select the most significant ones,
- the direct comparison between the non-repaired joint and the repaired joint thanks to a stress ratio.

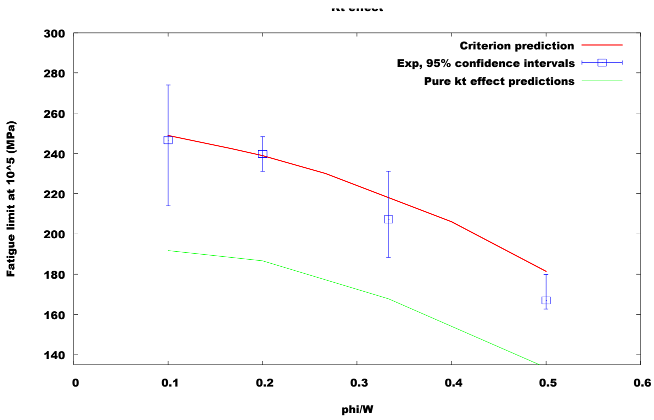
The experimental design used consists in creating several parametric studies according to the "Taguchi" theory. Preliminary results have shown that only adjacent holes are impacted (limited Kt increase as a function of the pitches and thicknesses mainly). The influence on the distant holes is negligible (transferred loads not disturbed). This study will be further extended and refined in order to establish engineering specifications and stress justification methods.




### 6.1.4. Gradient effects and scatter: modelling fatigue in stress concentration areas (EADS IW)

The work on fatigue started from the observation that fatigue criteria, which are widely used for engineering analysis, do not account for the effect of stress gradient on fatigue resistance, although it is well known that the local peak stress alone is not sufficient to correlate fatigue data (i.e. for a given maximum load, the fatigue life is known to be different for a plane tension or a bending case). Considering that most of the proposed approaches to account for this effect are not easily transposed to structural analysis (mainly due to conceptual difficulties to extend them to truly multiaxial load cases), EADS IW formulated an original non local fatigue criterion, based on a two-level approach (meso and macro level) similar to Papadopoulos. The identification of the parameters of the model requires only one more type of tests than the classical criteria (such as Crossland or Dang Van), and was demonstrated to be robust with respect to the tests chosen for the identification.

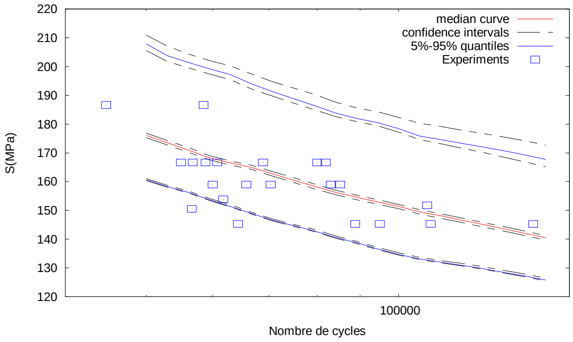
**Effect of hole diameter to specimen width ratio on fatigue allowable (for given life)**



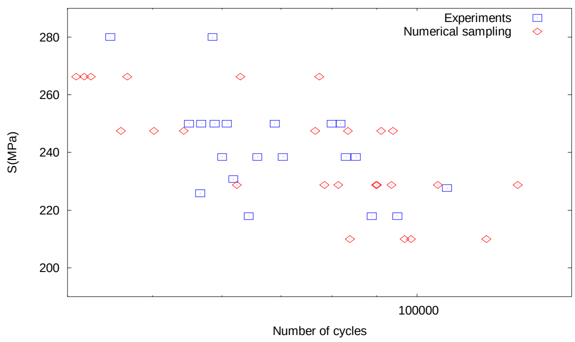

The proposed criterion accounts for gradient effect, as illustrated on the figure above on an aluminium alloy, where the predicted influence of the hole-to-width ratio on the fatigue life of open hole coupons matches the experimental data (dots with error bounds), while a prediction based only on a stress concentration correction from plain specimen fatigue data clearly fails and by far underestimates the fatigue allowable (see [1] for more details).

The predictive capabilities of the approach have been further evaluated by computing several constant life diagrams and/or whole SN curves for several kinds of loadings and stress gradients. The predictions are then compared either to experimental data obtained from dedicated testing on an aluminium alloy or from the literature. The relative error between experimental fatigue limit (considered at 105 cycles) and prediction of the proposed model for various configurations (open-hole coupons, plane specimen for tensile testing, four-point plane bending specimen) falls within 5%.

As the criterion was shown to be relatively accurate, a stochastic version was derived, following a classical probabilistic approach with propagation of uncertainty, and using a single random variable to account for uncertainty (which was validated a posteriori by sensitivity analysis; more details in [2]). The identification of the random variable distribution was shown to be robust with respect to test type. With this model, the ability to simulate Wöhler curves with a predicted scatter similar to that of experimental data (for a testing series not used in the identification procedure) was demonstrated (next figure right). Additionally, quantiles with confidence intervals could be predicted, which compared fairly well to available experimental data (next figure, left).




**Exp. Data and predicted curves with confidence intervals**




**Standard deviation predicted matches std. dev. Observed on different test configuration different form identification**

Some more detailed results may be found in the poster "Towards robust fatigue assessment: a probabilistic stress-based fatigue criterion accounting for gradient effects", which has been prepared and presented by EADS IW and EMAC in the poster session of the 24th ICAF Symposium

References :

1. C. Schwob, F. Ronde-Oustau, L. Chambon, Fatigue crack initiation in stress concentration areas, 16th European Conference on Fracture, July 3rd-7th 2006

2. C. Schwob, L. Chambon, F. Ronde-Oustau, J-P Bernadou, Probabilistic assessment of fatigue life using a stress-based fatigue criterion, 8th International Conference on Computational Structures Technology, Las Palmas de Gran Canaria (Spain), Sept. 12-15th 2006

### 6.1.5. In-service flaws: fuselage dents (EADS IW)

This activity deals with fatigue life predictions. The industrial objective is to be able to extend the allowable dent size in structures. The research objective was to take into account the residual stresses and the 3D geometry that are induced by the presence of the dent in the fatigue life prediction.

Concerning the prediction of the fatigue life of dented coupons, a full 3D finite element approach (using Abaqus) was developed at EADS IW, simulating the denting process and computing a multiaxial fatigue criterion over the stress tensor components. It was reported in 2005 to yield satisfactory fatigue life predictions. In this approach, the criterion is computed at nodes. During the last two years, improvement was sought to deal with stress gradient and other multiaxial fatigue criteria.

A first approach was investigated, indirectly dealing with stress gradient and computing Crossland fatigue criterion. The needed inputs are: a material Wöhler curve obtained on a standard specimen (in this case an open hole specimen was chosen because of similarity of the stress gradient with that of a dented coupon) and a few dented coupon tests results obtained under a given fatigue stress. 3D finite element calculations are carried out to derive the stress tensor on each specimen geometry (open hole and dent), for the fatigue life given by the dented coupon tests. Crossland multiaxial fatigue criterion has been implemented in the FE code and computed in the FE calculations of both geometries. Shear stress τ and hydrostatic pressure P involved in the fatigue criterion are then calculated and plotted in the fatigue diagramme. This allows to derive the α and β parameters of the material criterion line for the given fatigue life (this line joins the results obtained on the standard specimen and those on the dented coupon for the same fatigue life). The figure below depicts the approach.

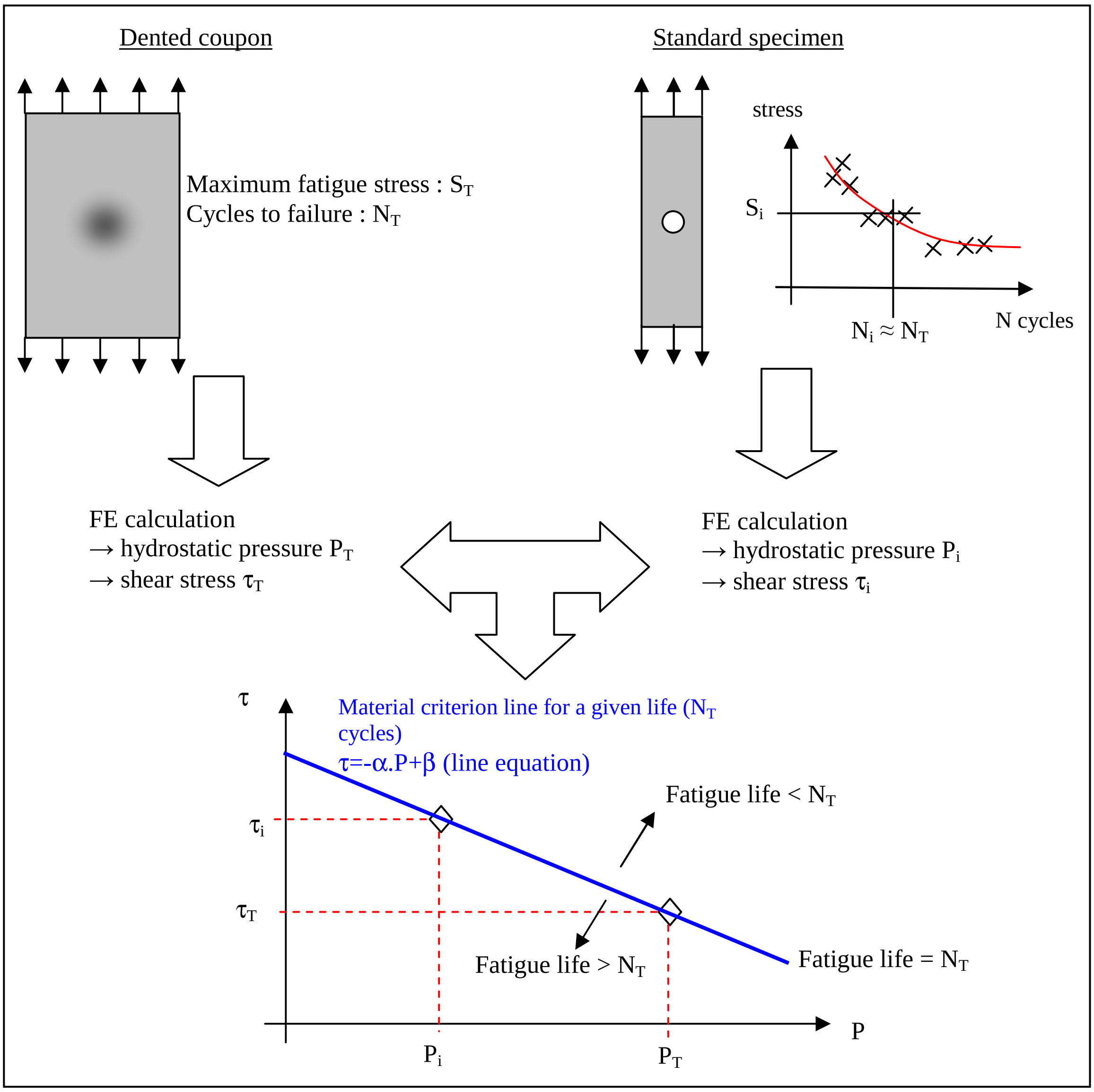
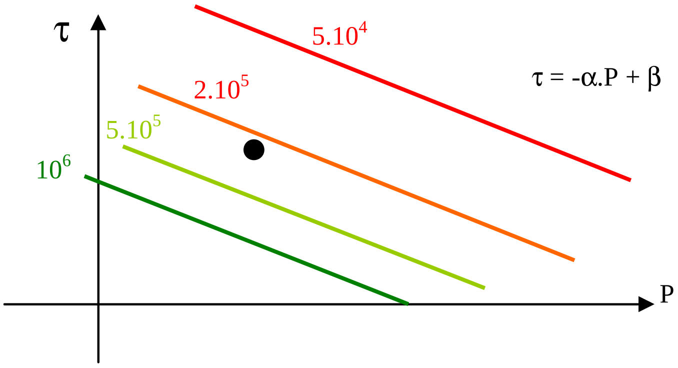
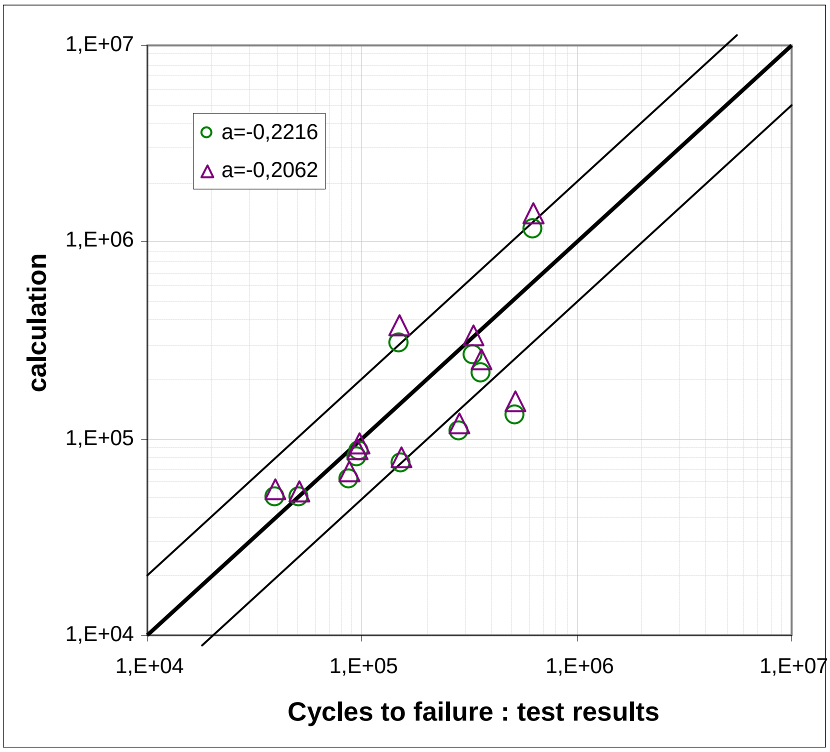



*Figure 1 : Identification principle of α and β coefficients for fatigue criteria*

Under the assumption that for other fatigue lives, the criterion lines are parallel (same α slope), a network of parallel lines associated to different fatigue lives can thus be derived in the (P, τ) diagramme from the single Wöhler curve obtained on the standard specimen. This network can then be used to assess the fatigue life of dents. The FE analysis results of any dented coupon are thus denoted by a solid point as shown in the plot below. The programme then calculates the fatigue life from the relative position of the dot to the nearest lines.




The comparison of predictions against tests results obtained in IARCAS project [1] concerning dented coupons made out of 6056 alloy, 1.2 and 2.2 mm thick, dent depth ranging from 5 to 20 mm, under different sets of fatigue stress show a fairly good agreement.




A second approach is under progress. It proceeds with the stress gradient approach that has been presented above including scatter effect. Preliminary results are fairly good (similar to those obtained with the above approach), but need to be further analysed (in particular the behaviour of the criterion has to be monitored at the macro level).

References :

1. IARCAS project "Improve and Assess Repair Capability of Aircraft Structures". Growth Project GRD1-2000-25182, 5th Framework Programme of the CEC

### 6.1.6. Fatigue life evaluation on aluminium alloy part after unbending by cold forming (LATECOERE)

After machining, large aluminium aircraft parts like bulkhead frames (see figure 1), beams, etc, could have residual distortion. This fact is due to new internal stress equilibrium after material removal. Some of these distortions are not allowable for a normal aircraft operating assembly conditions. In this case, the part could be unbent by a cold forming process, like three points bending beam (see figure 2).

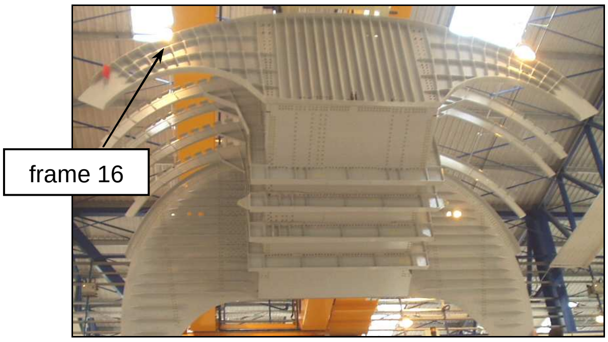



*Figure 1 : Example of concerned part : frame 16 (A380)*

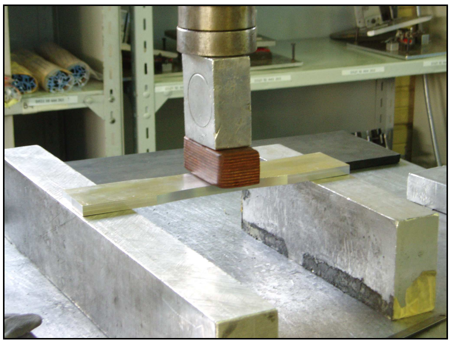


*Figure 2 : Sample unbending process*

But, this process induces internal residual stress field in the part, which allow the new acceptable flat shape.

The goal of this study is to evaluate if these new internal stress field could have an impact on fatigue live. The chosen approach, as a first step, is based on a basic case (flat sample in 7175 T7351) to avoid dispersion or uncertainty associated to a more complex structure. Stress level tested is 380 MPa.

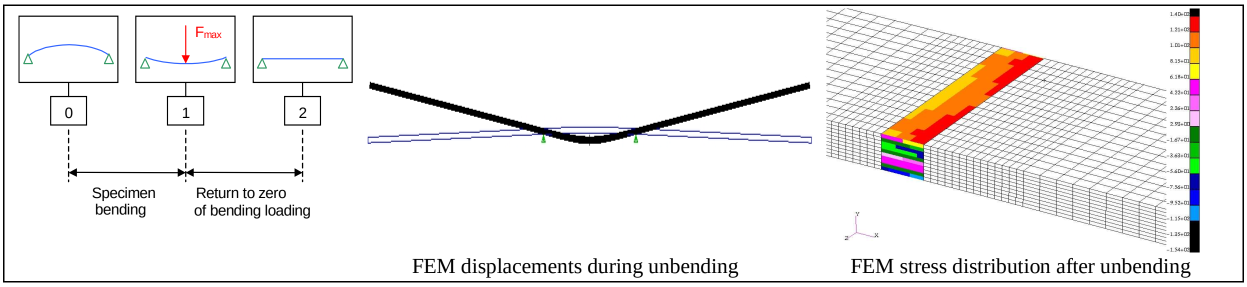



*Figure 3 : Sample unbending process 3D modelling*

Theoretical stress field obtained by unbending process 3D Finite Element modelling (see figure 3) is compared with measured stress by X-ray diffraction on sample. The correlation obtained is acceptable, thus the sample unbending phase modelling is verified.

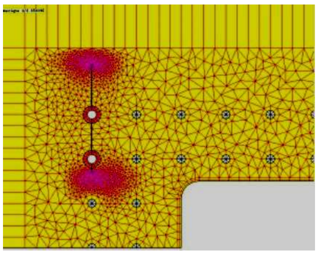
The calculated fatigue lives of different samples (by conventional unidirectional approach and by multi-axial approach) are compared successfully with tested sample fatigue lives. Based on the fatigue tests made, we can conclude that the residual internal stress field has a negligible impact on fatigue life, due to material adaptation. The maximal theoretical peak stress and the new stress ratio R after unbending process does not drive the fatigue life in the present study for the S/N curve area around 40,000 cycles for 7175.

This test program gives answers for our specific studied case, but should be extended to higher fatigue life and other material.

## 6.2. COMPUTATIONAL TECHNIQUES

### 6.2.1. Damage tolerance calculation advanced methods for fastened repair solutions (Airbus France)

In-service repairs on a primary structure of an aircraft are usually performed by the airlines according to the repair solutions provided in the Structural Repair Manual. Consequently, the aerospace industry has to enable a simple evaluation of damages and to provide repair procedures that are safe, less time consuming, simple to perform, inexpensive and durable as much as possible. As the reduction of downtimes is the highest priority of the operator, an increase of allowable damage size could be a big improvement for the airliner to reduce this time penalty or the aircraft on ground situations that can also disturb the complete flight schedule and lead to even big delays in the air traffic. Designing for damage tolerance includes also selecting materials that are inherently damage resistant, identifying sources and types of damages, understanding damage propagation mechanisms. Implementation of the optimal damage tolerance approach to structural integrity ensures that flaws or cracks that may exist in the structure will not grow to a critical size and cause catastrophic failure within specific period, such as a safe inspection interval.



Crack growth of fatigue cracks initiated in 2024-T351 and 2524-T351 from several repair solutions was analysed. In the framework of a European research program, improved Damage Tolerance calculation methods, based on Finite Element Analysis, were developed for fastened limited and unlimited (cut-out size more than one stringer and frame bay) repair solutions. This approach is based on Samcef software using Mecano non-linear solver that permits to idealise all skin repairs, to take large displacements into account, to consider biaxial loading and to optimize the CPU time. For these calculations, the use of crack tip elements allowed the evaluation of the Stress Intensity Factors, thus fatigue crack growth. What is new is the modelling of the crack tips and fasteners where the bore is cracked. All cracked bores were modelled with solid elements to take into account the pin load (greatly influencing SIF especially for small cracks) as accurately as possible. Regarding crack tip, it can therefore be located in volume-meshed area or in a shell-meshed area. In the small cracks case, Barsoum 3D elements were simply added in the part meshed with volume elements (figure 1). In the second case, Barsoum 3D elements were added too in order to be able to represent the variation of SIF through the thickness, taking into account the bending effects. These elements were linked to shell ones by specific elements following the same approach used to link volume fasteners to the plates (figure 2). These two principles were then used at the same time in order to cover a great number of configurations and reduce CPU time (figure 3).

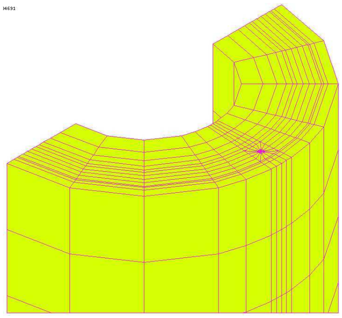


*Figure 1 : example of cracked bore including 3D Barsoum elements*

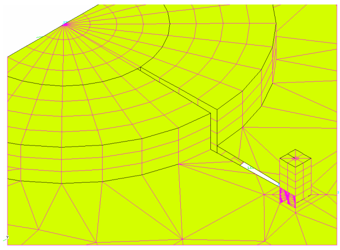


*Figure 2 : view of crack with tip is in the shell-meshed plate*

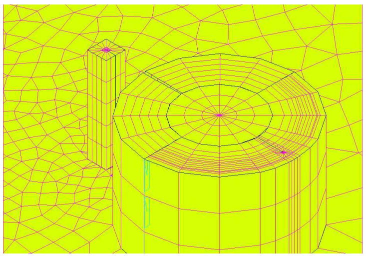
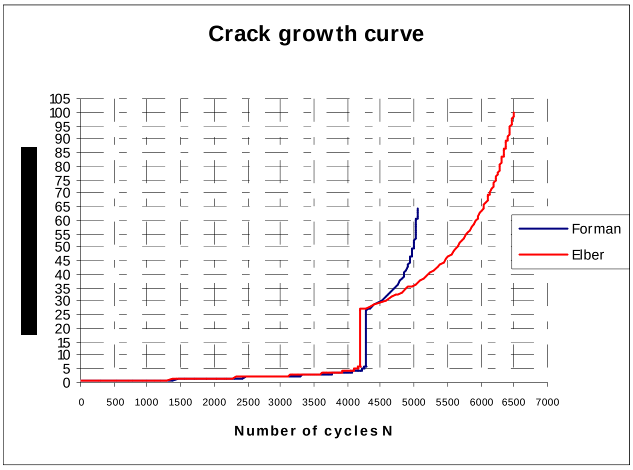
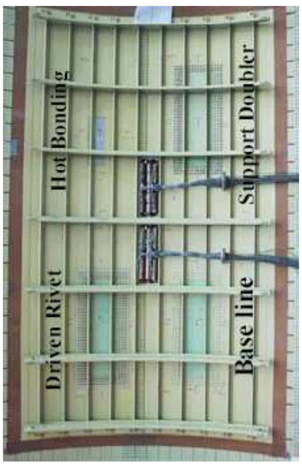


*Figure 3 : zoom on a fastener with a bore cracked on both sides*

Associated to Forman or Elber's behaviour laws and to an adequate cracking scenario, the Repeated Inspection Intervals were calculated for several repair solutions. In parallel, experimental tests were conducted on flat un-stiffened and stiffened panels as well as curved (representative of A340 fuselage radius) pressurised panels to validate the FE models described above.

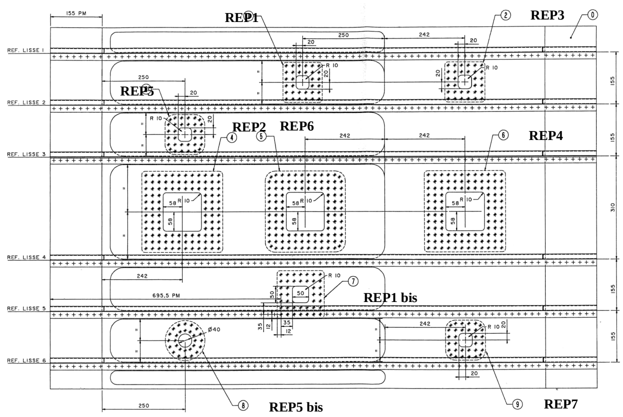



Each panel had at least one repair solution introduced and they were subjected to constant amplitude fatigue loading at stress ratio (Smin/Smax) R=0.1. Each flat un-stiffened panels contained a single repair; the cut-out size (limited and unlimited repair) as well as new repair techniques (such as the use of an internal doubler to reduce the secondary bending) were investigated in Damage Tolerance. Each flat stiffened panel had several limited repairs (up to nine repairs) introduced and the influence on fatigue crack growth of the position between repair and stringers were investigated.

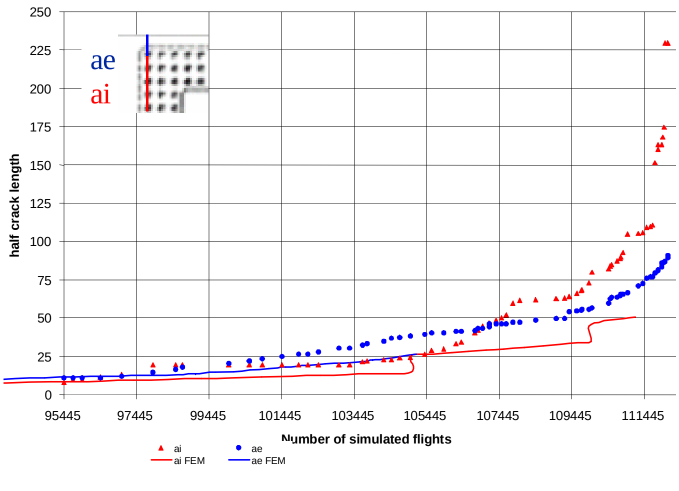


Each curved stiffened panel contained four un-limited repairs: a baseline repair (according to the Structural Repair Manual, SRM) and three advanced repair solutions (two fastened and one hot bonded). These panels were subjected to cycling internal pressure and longitudinal load at stress ratio R=0.1. The influence of the biaxial loading condition (combined internal pressure and longitudinal load) on the crack growth of fatigue crack emanating from each repair was investigated: gain of 17% on the inspection interval was found while taking into account this parameter. While the skin is in 2524, the crack propagates more slowly than in 2024, allowing a multiplication of the inspection interval.

Flat un-stiffened panel tests containing limited repair solutions with Glare® doublers exhibited slower crack growth when compared to repair solutions containing aluminium doublers. It was concluded that the lower stiffness of the Glare® doubler, which causes less load attraction into the repaired area than in case of the aluminium doubler with comparable connection stiffness (i.e. fastener system), were the main responsible of lower crack growth rates. As the load twists the Glare® doubler, the surrounding structure has to be watched carefully.




In flat panels containing limited repairs, it was found that fatigue cracks preferably initiated from the fasteners in the corner of the repair. For this reason the cracking scenario considered in the FE models is a double-side through-the-thickness detectable cracks emanating from the 4 fasteners located in the corner of the repair. A total of eight cracks are considered simultaneously. Calculations and crack propagation measurements highlighted that Finite Element Analysis associated with this realistic cracking configuration is less conservative and more representative of the real structure than current analytical calculation methods. The crack scenario considered could be realistic. The repair geometry had few influence on the crack propagation. The higher the load level, the smaller the inspection interval (the inspection interval increases of 35% when the load decreases of 15%). The inspection intervals obtained by numerical method are 5 to 8 times superior than analytical results.




As a consequence, inspection intervals are increased and maintenance costs reduced. This Finite Element based models have been implemented in AIRBUS F&DT calculation tool.

### 6.2.2. Investigation of bolted/bonded joining technology (Airbus France)

The study deals with the application of the hybrid (bolted / bonded) –quoted HBB–- joining technology on aircraft. This process is firstly focused on the most relevant and easiest application: the longitudinal metallic-to-metallic joints of fuselage. Nowadays these particular joints are mainly 3 fasteners lines single-lap bolted joints; an interfay sealant layer is added between both plates. The objective of this research work is to replace classic joints by 2 fastener lines single-lap HBB joints. This is achieved by removing 1 fastener line and replacing the current interfay sealant by a structural sealant. As the new design fulfils generally the static design criteria without taking bonding into account, the fatigue strength appears as the most critical design criterion.

A preliminary study on the mechanical behaviour of the HBB joints has been performed. Three approaches have been used: analytical, numerical and experimental. A range of parametrical tools were developed to calculate the distribution of loads transferred by both fasteners and adhesive as a function of the mechanical and geometrical parameters. Simplified 1D and 2D analytical models were developed which assumed an isotropic elastic behaviour of materials. They are based on the creation of new finite elements especially formulated to simulate both bonded adherends. The local mechanical behaviour, e.g. fastener stiffness required in the analytical approaches, is investigated with a 3D numerical model (figure 1. The experimental measurements of transferred loads under moderate applied loads validated and calibrated the analytical and numerical calculation approaches, whereas fatigue tests showed potential large benefits in fatigue life

In order to be able to apply the HBB joining technology using structural sealants, the four following specifications are required to be considered in parallel: the product qualification, the industrial process qualification, the structural strength justification and the assurance quality process. In the frame of the product qualification, the objective is to show that the structural sealant is able to ensure the same functions as the ones of the current one as well as to fulfil its new function of participation in the joint mechanical strength. This shall be ensured throughout time. In the frame of the industrial process qualification, the objective is a transparent way in the replacement of current sealants by the structural ones across the manufacturing process. In the frame of the structural strength justification, two complementary directions are examined: the validation of the HBB joints with new products and, the R&D to develop predictive design prototypes. In the frame of the insurance quality process, the objective is to define a reliable and robust industrial process enabling the industrial application of the bonding technology.

The key points of the mechanical strength justification are:

- the accurate mechanical properties characterization of the structural sealants to model its behaviour in single-lap joint configurations;
- the demonstration of the mechanical strength of HBB joints under fatigue loads;
- the consideration of possible environmental degradations.

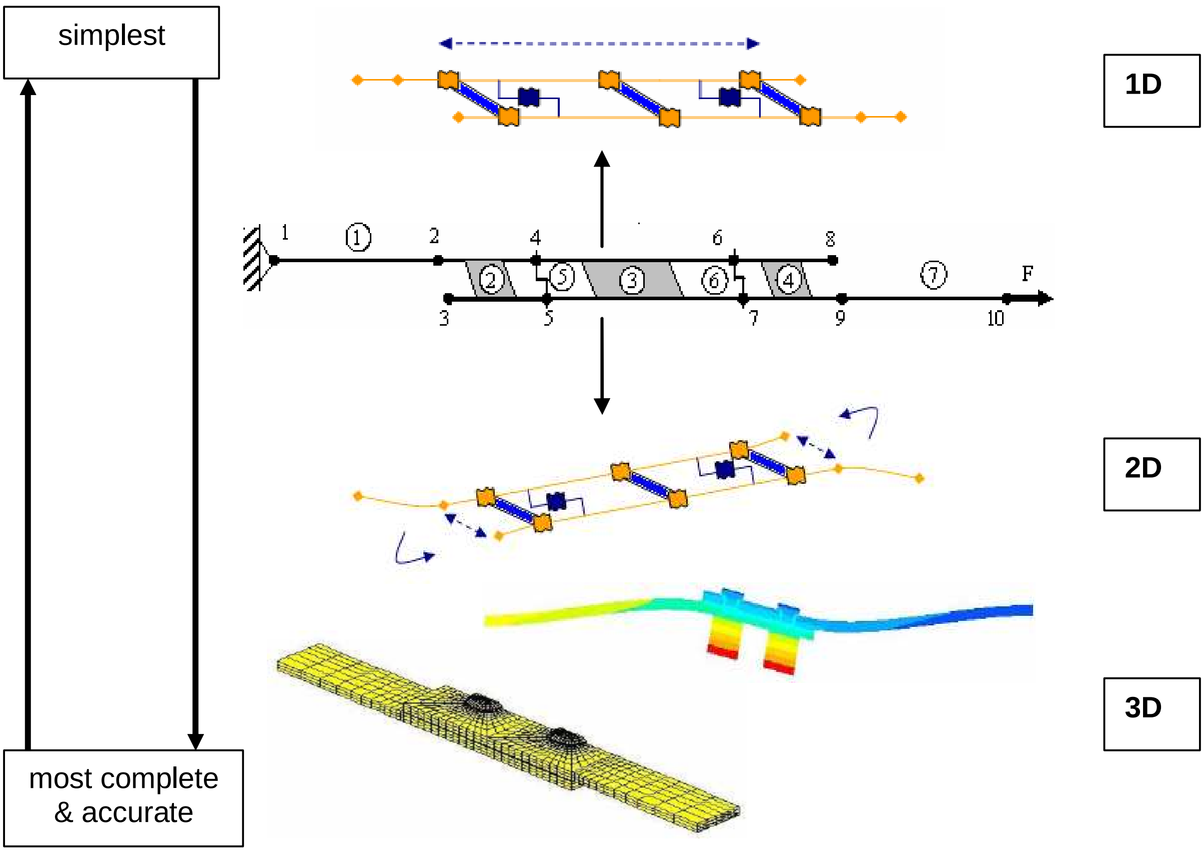



*Figure 1 : Multi level simulations of the HBB joints mechanical behaviour*

### 6.2.3. Spectrum loading: PREFFAS model (EADS IW)

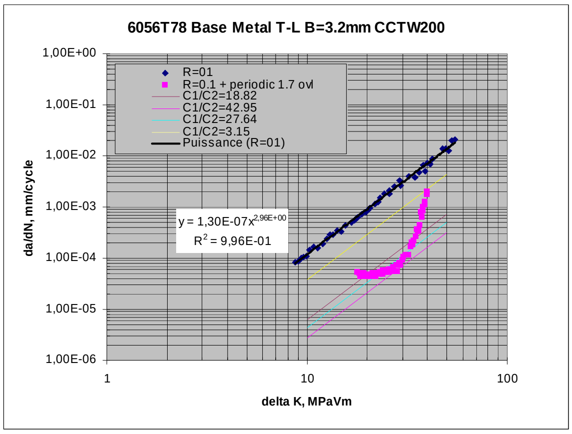
The parameters of PREFFAS model are usually determined through two fatigue crack growth tests: a constant amplitude loading test (R=0.1) and a periodic overload test (1.7 overload every 1000 baseline R=0.1 cycles). An assumption states that the two crack growth rate curves must be parallel. PREFFAS model has been integrated into CRACK-KIT® software to calculate crack growth under spectrum loading.

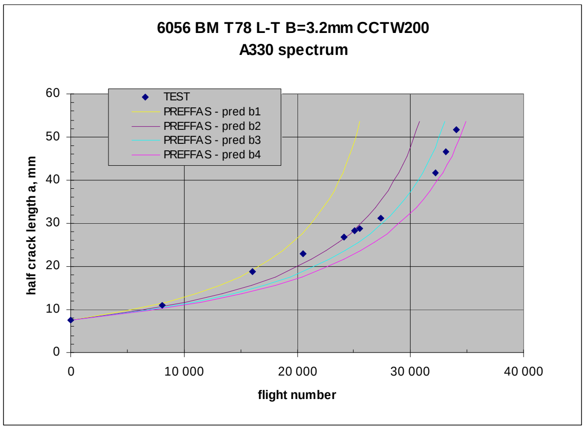
CRACK-KIT/PREFFAS software has been used to predict fatigue crack growth under spectrum loading on 6056 alloy, 3.2 mm thick in IDA project [1]. The two baseline tests were run plus one under spectrum loading (A330 fuselage) to verify the predictions.

The results show that with an overload ratio of 1.7, it is not easy to identify the parameters because the retardation curve is not straight. If the parallel line is chosen close to the bottom part, one ends up with a fairly good prediction (predictions b2, b3 and b4).

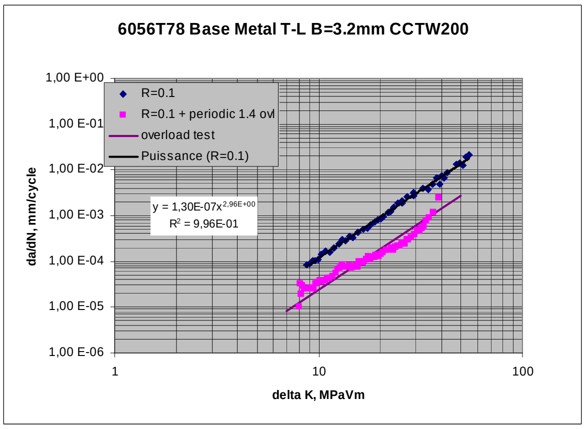
**PREFFAS retardation analysis**

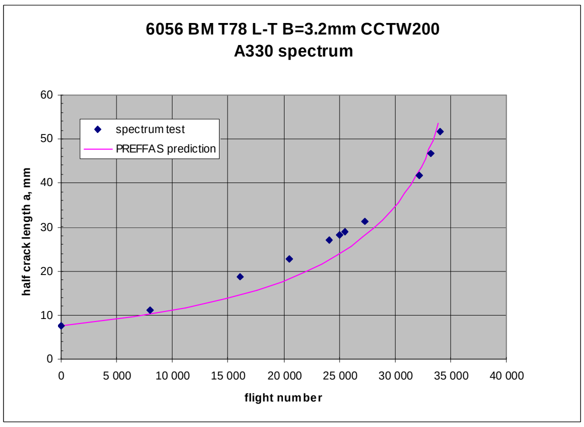
| | | | | |
|---|---|---|---|---|
| B | 0,53 | 0,48 | 0,5 | 0,69 |
| A | 0,47 | 0,52 | 0,5 | 0,31 |
| EQUI | 3692 | 3259 | 3440 | 4455 |
| prediction | pred b2 | pred b4 | pred b3 | pred b1 |




Additional tests were run using a lower overload ratio of 1.4. In this case, the retarded curve is straight and parallel to the R=0.1 test. The identification of the model parameters is then straightforward and ends up with a fairly good prediction: A=0.51, B=0.49 (which are close to those related to b3 prediction).




It is thus recommended to proceed with an overload ratio of 1.4 on thin sheets of aluminium alloys to identify PREFFAS.

References :

1. IDA project “Investigation on Damage Tolerance Behaviour of Aluminum Alloys”. Growth Project GRD1-2001-40120, 5th Framework Programme of the CEC.

### 6.2.4. R curve simulation on thick sheets: an FE based simulation (EADS IW)

The industrial goal is to have at disposal, through simulation, large R curves for a wide range of thickness of sheets. The research goal is to implement failure criteria to extrapolate R curves. EADS IW has developed an approach to simulate the residual strength of coupons (R curves) or that of stiffened panels [5]. The approach is based on 2D elastoplastic finite element analysis, which implements a local failure criterion ahead of the crack tip in order to simulate the crack advance under the applied load. The local failure criterion derives from a local approach of fracture such as the Rice and Tracey model of cavity growth to describe the ductile rupture. This method does not suffer from any limitations such as those met by the usual methods which are conducted within the frame of linear elastic fracture mechanics.

The Rice and Tracey cavity growth law reads as, R denoting the cavity radius:

$$Log(\frac{R}{R_0}) = \int_{p_n}^{p} c_1 \times e^{(\frac{3}{2}\times\frac{\sigma_m}{\sigma_{eq}})} dp$$

$p_n$ : equivalent plastic strain

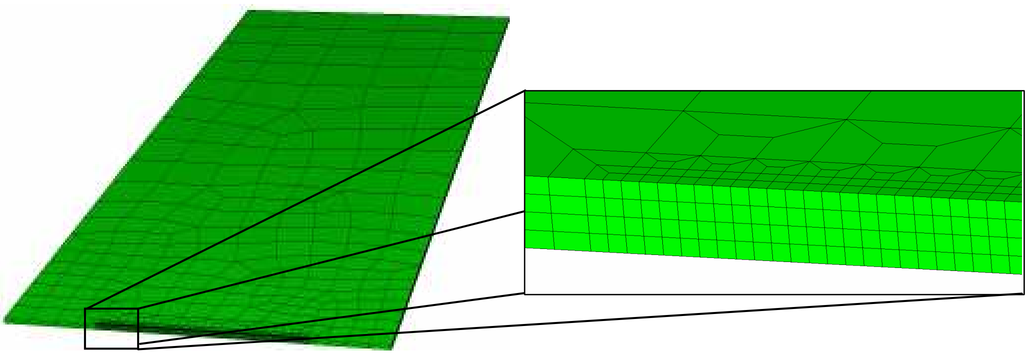
$$\sigma_m = \frac{\sigma_{11} + \sigma_{22} + \sigma_{33}}{3}$$

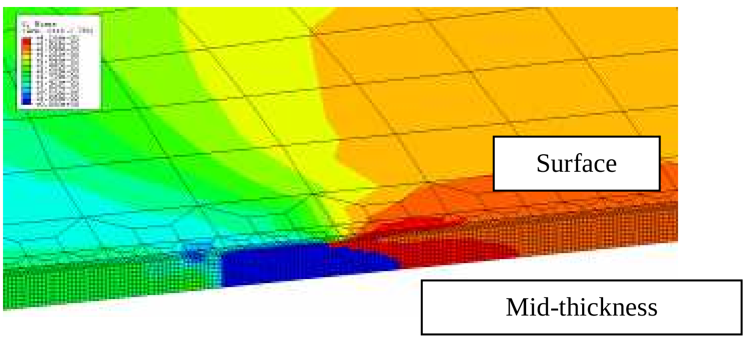
$\sigma_{eq}$ : Von Mise stress

(R/Ro) is computed at the crack tip. If a critical value, denoted by (R/Ro)c, is reached, then crack growth takes place over the elements with (R/Ro)> (R/Ro)c. And so on for further load steps until failure of the specimen. Thus only one parameter that accounts for ductile failure is needed: (R/Ro)c.

The extrapolation scheme is as follows: identify (R/Ro)c on a small R curve, simulate a larger R curve using the same (R/Ro)c value.

The 2D method, under plane stress condition, has proved to be successful on thin skins (up to 3 to 4mm) for extrapolating R curves or simulating the residual strength of welded stiffened panels [5]. The effort has then focussed on larger thickness of sheets, resorting to 3D FE calculations since plane stress is no more prevailing. Development work to implement a 3D approach with Abaqus code has been carried out. First obtained results are presented herein. The figure below shows a 3D meshing of 1/8 of a CCT specimen due to symmetry reason.






The validity of the 3D approach was checked on simulating R curves on thin sheets of 2024 (1.8mm) or 6056 (3.2mm) alloys as reported in the following table.

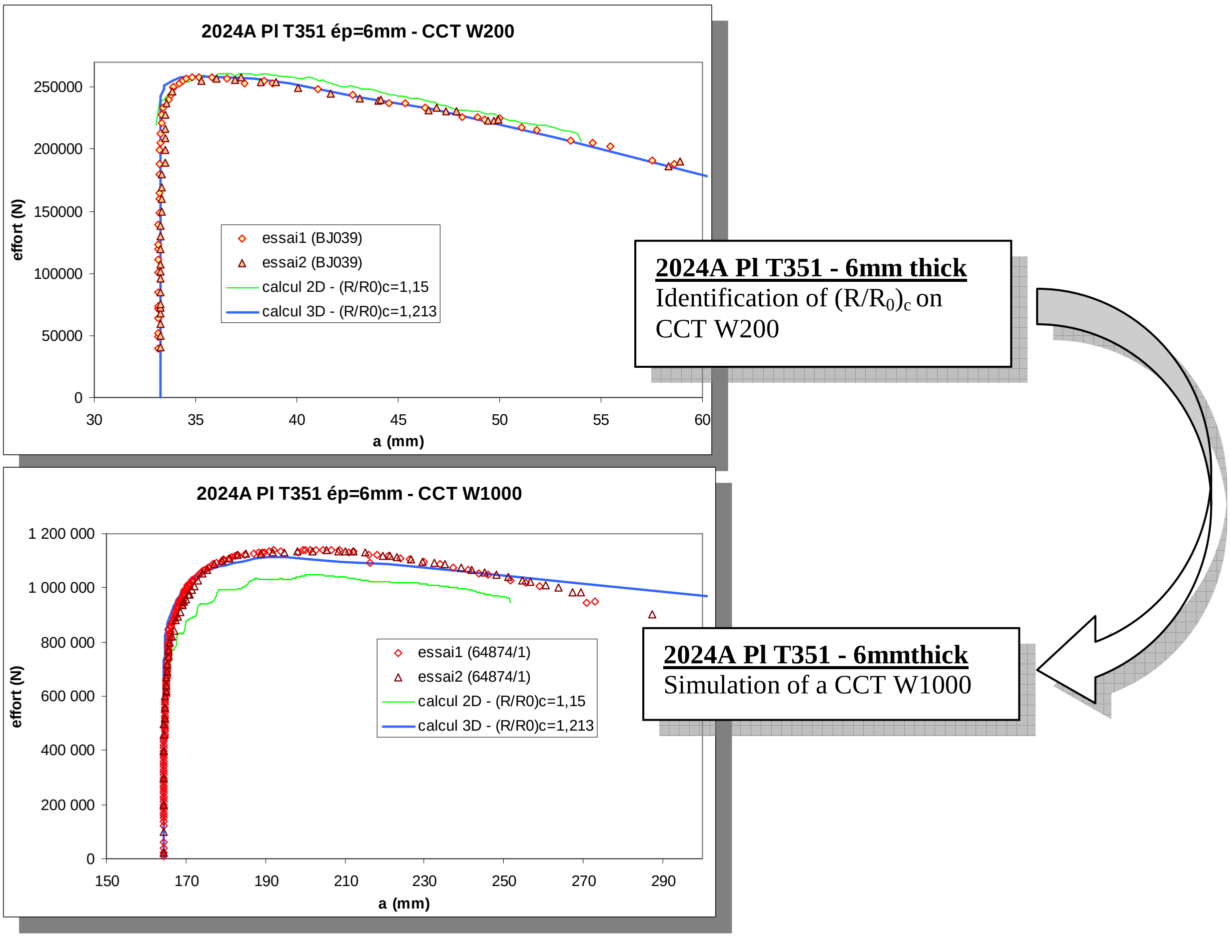
| | simulation | specimen | **Relative difference between simulation and test data in failure load** | |
|---|---|---|---|---|
| | | | 2D simulation | 3D simulation |
| 2024A plated T3 1.8mm | Identification of failure parameter | CCT W=160mm | -1.4% | +0.6% |
| | extrapolation | CCT W=400mm | +2.1% | +1.0% |
| 6056T78 3.2mm | Identification of failure parameter | CCT W=400mm | +1.3% | +0.1% |
| | extrapolation | CCT W=760mm | +1.3% | +0.1% |

Both the 2D and the 3D simulations give fairly good results. For these thicknesses, any small R curve may be extrapolated to larger ones, using the 2D or the 3D simulation.

Then the simulation approach was applied to same alloys with thickness of 6mm. A similar scheme was followed: identification of the failure parameter on a small size CCT W=200mm and prediction of the R curve on a larger size CCT W=1000mm.

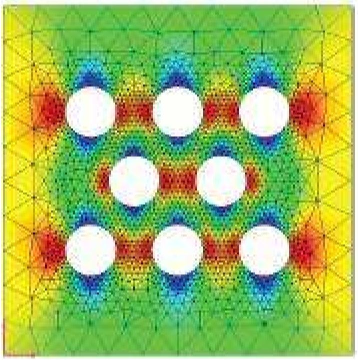
The results on 2024 show that the 3D simulation is necessary in this case as the 2D underestimates the experimental results on W=1000mm. The 3D approach is thus promising. However, on 6056 alloy, the 3D simulation underestimates the failure load on CCT W1000 by 15%. Work is ongoing to clarify this.

| | **simulation** | **specimen** | **Relative difference between simulation and test data in failure load** | |
|---|---|---|---|---|
| | | | 2D simulation | 3D simulation |
| 2024A plated T351 6mm | Identification of failure parameter | CCT W=200mm | +1.1% | +0.3% |
| | extrapolation | CCT W=1000mm | -7.9% | -2.3% |

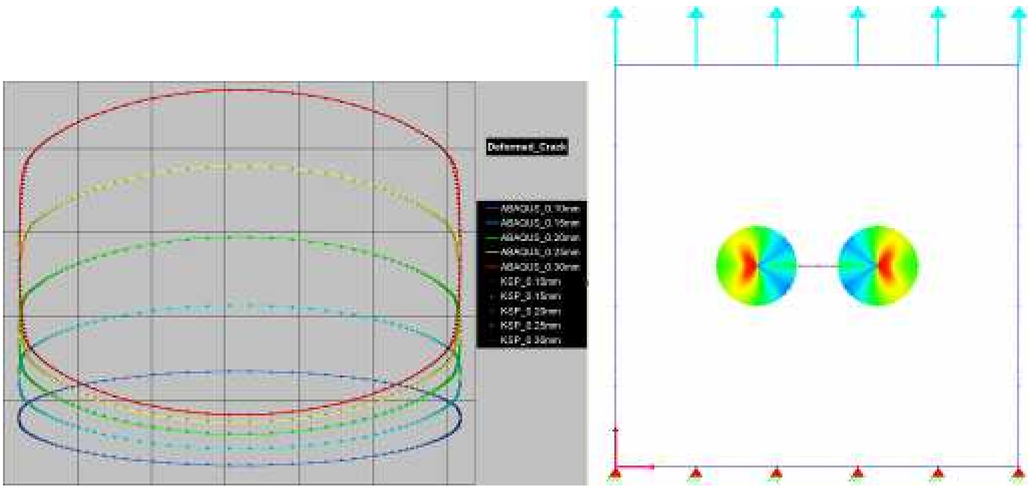



### 6.2.5. Modelling of ductile tearing of thin light alloy skins: a BEM based simulation (EADS IW)

Following the application of a local approach to the prediction of the R-curve for CCT specimens and the residual strength of stiffened panels [1], within a commercial FE code (Abaqus), the same type of analysis was investigated using the dual boundary element method (DBEM) [2]. The idea is to ease the meshing constraints at the crack tip, by taking advantage of the accuracy of the DBEM for relatively coarse, unstructured meshes. For illustration, we have represented on the figure below the tension field for an elasto-plastic analysis of a plate with multiple holes.



A more representative problem is the CCT coupon, for which example computations are presented in the figure below. On the left, the crack opening (dots) is compared to a finite element reference (solid curve), with a non linear material behaviour (hence the characteristic blunt shape) for different load level. On the right, the crack tip stress field is represented (with the use of a local interior mesh, as allowed by the DBEM), with the characteristic "bean" shape. Qualitative and quantitative comparisons have proved excellent so far. The tuning of a local approach, as described in [1], is in progress to validate the approach on experimental data.



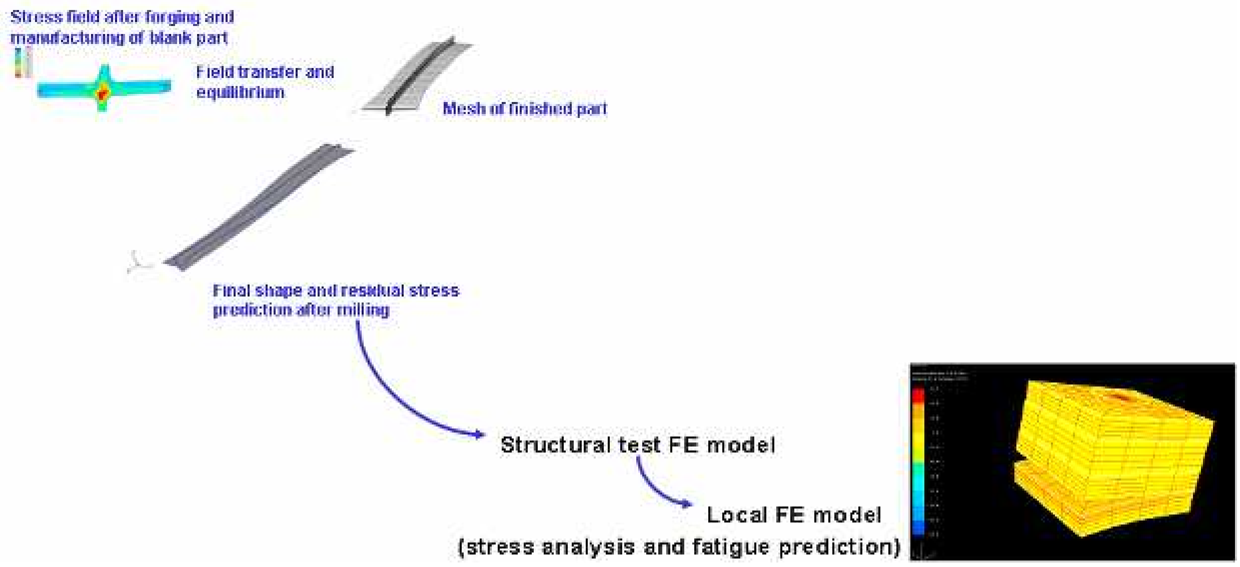
References :

1. F. Congourdeau, B. Journet, C. Meyer, Damage tolerance of fuselage welded stiffened panels, ICAF 2003 « Fatigue of Aeronautical Structures as an Engineering Challenge », 22nd Symposium of the International Committee on Aeronautical Fatigue (ICAF), Lucerne, Switzerland, 5-9 may 2003

2. G. Hello, H. Kebir, L. Chambon, J-M. Roelandt, A. Rassineux, Application de la méthode des éléments de frontière à la résolution de problèmes élastoplastiques, 7ème Colloque National en Calcul des Structures, Giens (France), May 2005

### 6.2.6. Simulation of large complex structures: a multiscale calculation chain (EADS IW)

The improvement of computational structural analysis methods is another major enabler of computationally intensive structural analysis. EADS IW has been active in the field of computational structural mechanics over the past two years. Examples of activity include the development of domain decomposition methods (including multiscale approaches, see [1], [2]) for the analysis of fuselage buckling, and developing a complete simulation chain (with Assystem and Airbus) to evaluate the influence of all the processing steps (from forging to assembly through milling). The latter study was carried out in a national project, and the aim was to evaluate the influence of residual stresses (due to manufacturing) and internal stresses (due to mismatch at assembly) on the fatigue performance of a fastened joint. The overall chain is illustrated in the figure below.




Some more detailed results may be found in the poster "Fatigue assessment of fastened joint including manufacturing and built-in stresses" prepared and presented by EADS IW, Airbus and Assystem in the poster session of the 24th ICAF Symposium.

References :

1. P. Cresta, O.Allix, Ch. Rey, On a mixed non-linear domain decomposition method and its efficiency for post-buckling analysis, US National Congress on Computational Mechanics, Austin, TA, 24-28 juillet 2005

2. P. Cresta, S. Guinard, O.Allix, Ch. Rey , Domain decomposition methods with nonlinear localization for post-buckling computation of slender structures, 7th World Congress on Computational Mechanics, Los Angeles, California, 16-22 juillet, 2006

### 6.2.7. A reliability-based study of corrosion-fatigue : application to the Alphajet aircraft (CEAT)

Airframe structural integrity in presence of corrosion is becoming an issue for ageing fleet. Fatigue damaging is effectively accelerated due to earlier crack initiation on corrosion damage. Reliability-based mechanical models (figure 1) of corrosion pit growth and fatigue crack growth associated with a pit to crack transition criterion and a failure criterion were set up and applied to the Alphajet aircraft corrosion-fatigue case (figure 2).

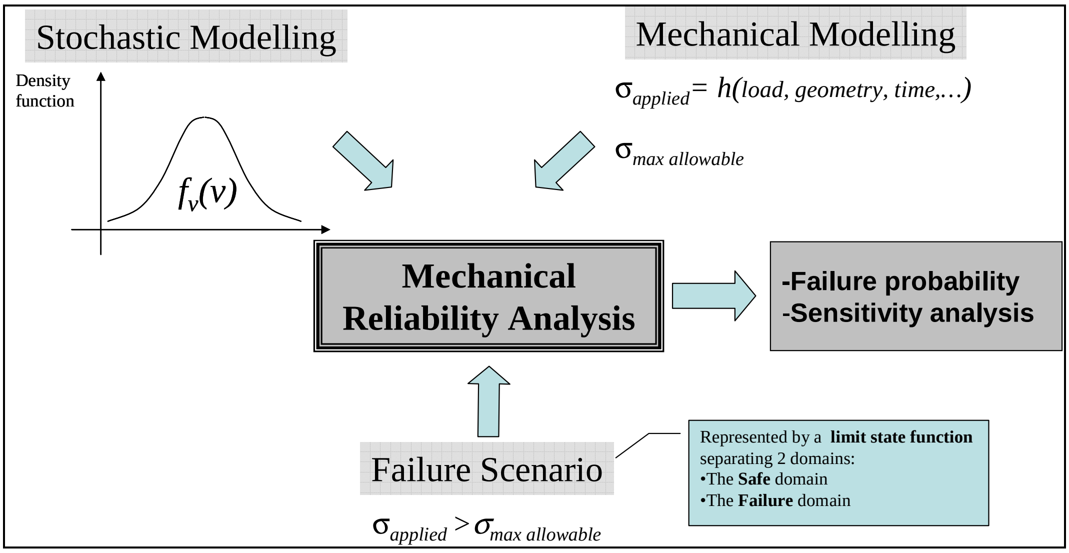



*Figure 1 : Mechanical Reliability Analysis principle*

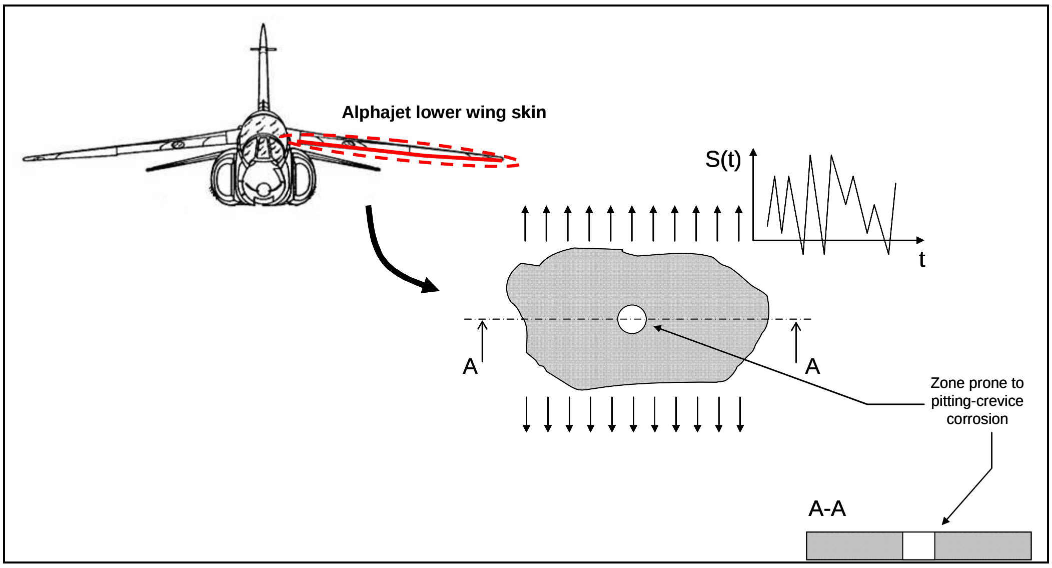
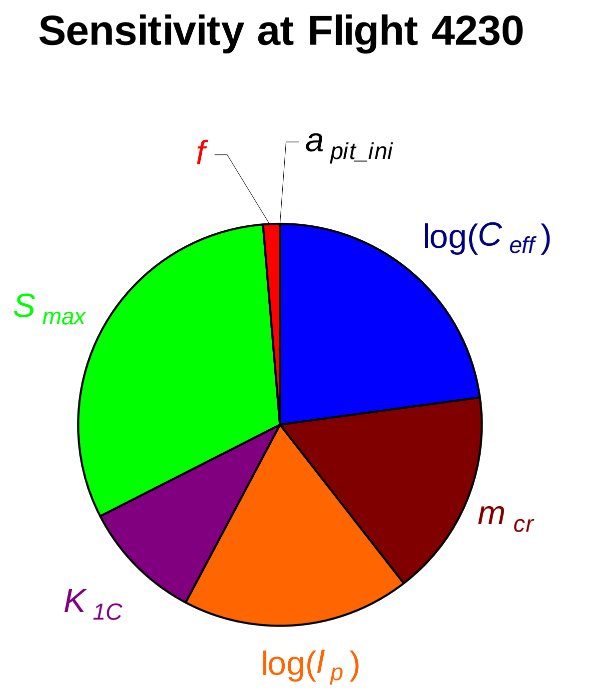



*Figure 2 : Alphajet corrosion-fatigue*

The probability distributions of the random variables and there correlations were determined through CEAT test database and the literature. This analysis reveals that a very high and negative correlation does exist between the Paris' law coefficients Ceff and mcr.

Reliability in function of number of flights is computed for several corrosion severities. A reliability sensitivity analysis is carried out for a moderate corrosion (figure 3). It appears that the reliability is relatively insensitive to the initial flaw size. Corrosion growth law, the rate of which is huge for small pit radius, explains the insensitivity to this random variable. A Risk Based Inspection approach in which the reliability is updated through the inspection is also proposed.




| | α |
|---|---|
| $a_{pit\_ini}$ | -1,69E-04 |
| $\log(C_{eff})$ | -4,83E-01 |
| $m_{cr}$ | -3,59E-01 |
| $\log(I_p)$ | -3,92E-01 |
| $K_{1C}$ | 2,02E-01 |
| $S_{max}$ | -6,66E-01 |
| $f$ | 2,86E-02 |

*Figure 3 : Sensitivity at flight 4230 (β=3)*

When compared with the deterministic approach, the proposed approach, which realises a realistic treatment of the uncertainties, appears to provide with highly rich and interesting information profitable for the decision-maker. Concerning the maintenance, one reveals that in the study case, with the associated assumptions, the first inspection step calculated through deterministic approach is very conservative regarding the target reliability. Maintenance strategies such as delaying a 'heavy' inspection without loosing in reliability through the set up of intermediate 'light' inspections is assessed. In the study case, almost a three years delay is achieved (figure 4).

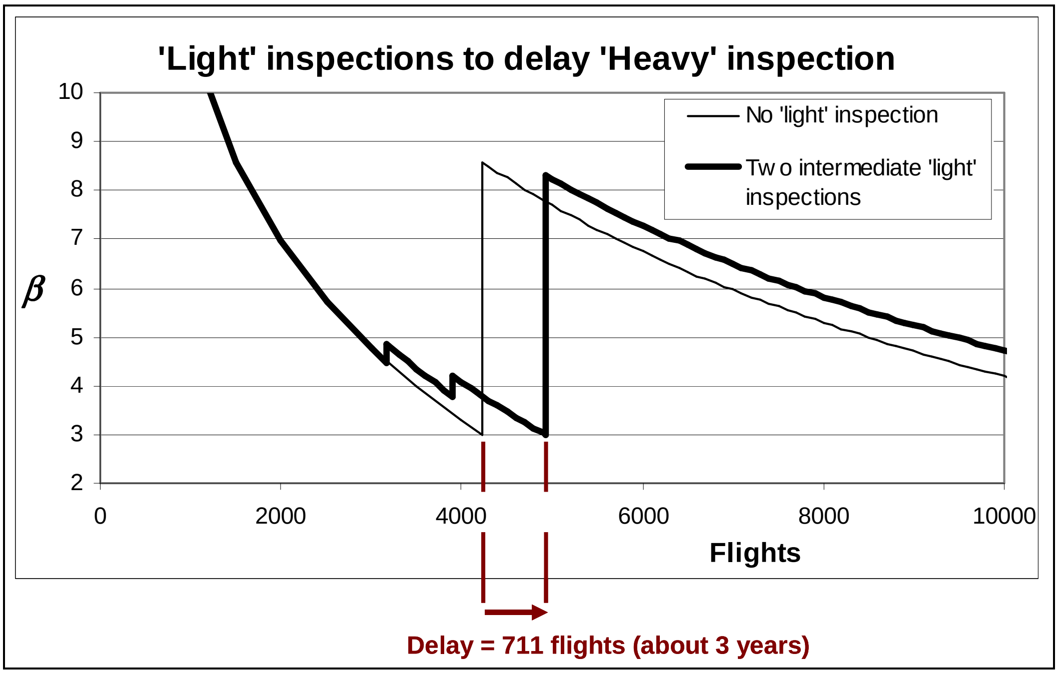



*Figure 4 : Two intermediate 'light' inspections to delay 'heavy' inspection*

### 6.2.8. Comparison of stress intensity factors measurements using digital image correlation with X-FEM simulations for plastic fatigue crack growth (CEAT and LaMCoS)

One presents a technique for the experimental measurement of stress intensity factors in cracked specimens under mixed-mode loading. This technique is based on full-field measurement using digital image correlation (figure 1) and an interaction integral. Such domain-independent integrals (figure 2) are often used in the finite element method to calculate stress intensity factors. The main advantage of this technique is that the errors made in the estimation of the measured displacement field near the crack's tip do not affect the measurement of the stress intensity factors.

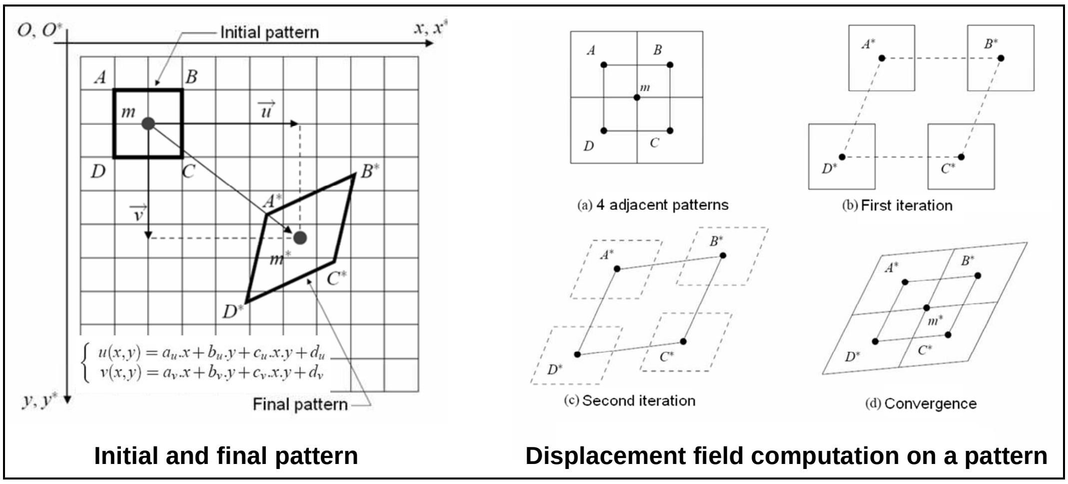



*Figure 1: Displacement field measurement by Digital Image Correlation*

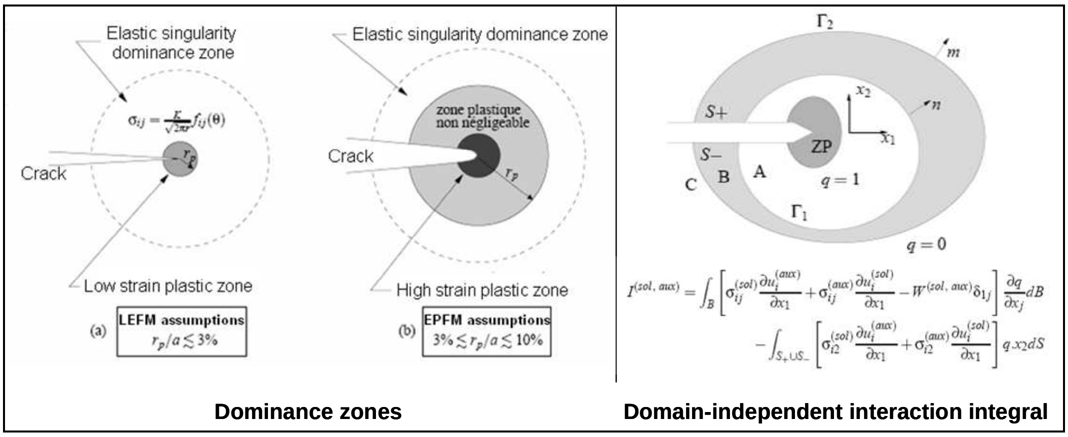



*Figure 2 : Dominance zones and interaction integral*

The capabilities of the method are illustrated through fracture measurements (figure 3) and compared with the eXtended Finite Element Method in order to simulate mixed mode plastic fatigue crack growth simulations with treatment of contact and friction (figure 4). The X-FEM uses the partition of unity in two ways: first to take into account the displacement jump across the discontinuity far from the crack tip, and second to enrich the approximation close to the front by considering the appropriate asymptotic fields [1,2].

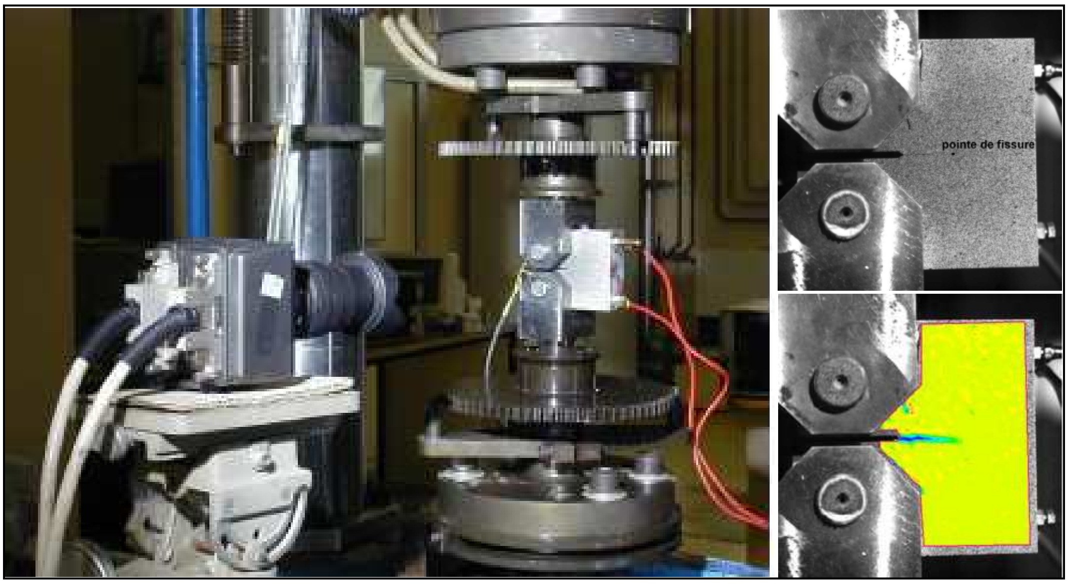
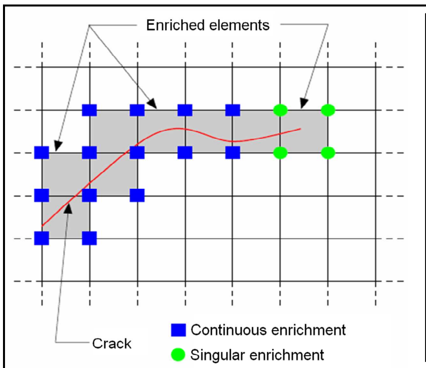



*Figure 3 : Digital Image Correlation applied to fatigue crack growth)*




**Extended finite elements approximation of displacement field:**

$$U = \sum_{i \in \mathcal{N}} N_i(\mathbf{x}) U_i + \sum_{i \in \mathcal{N}_{cut}} N_i(\mathbf{x}) H(\mathbf{x}) a_i + \sum_{i \in \mathcal{N}_{front}} \sum_{\alpha} N_i(\mathbf{x}) B_\alpha(\mathbf{x}) b_{i,\alpha}$$

**Elasto-plastic enrichment base**

$$r^{\frac{1}{n+1}} \left\{ \sin\frac{\theta}{2},\ \cos\frac{\theta}{2},\ \sin\frac{\theta}{2}\sin\theta,\ \cos\frac{\theta}{2}\sin\theta,\ \sin\frac{\theta}{2}\sin 3\theta,\ \cos\frac{\theta}{2}\sin 3\theta \right\}$$

*Figure 4: eXtended Finite Element Method in elasto-plastic assumption*

A mode I CT specimen was submitted to a cyclic tension loading with loading ratios from R=0.1 to R=0.7. One can notice the bumps on the crack faces after propagation due to the stress redistribution at the back of the succeeding tips (figure 5). Depending on the load ratio, these bumps will be responsible for possible crack closure as presented in Ref. [3], and will define the well known opening stress intensity factor that governs Paris law based fatigue crack growth. Finally mixed mode fatigue crack growth numerical examples are shown to validate the method (figure 6).

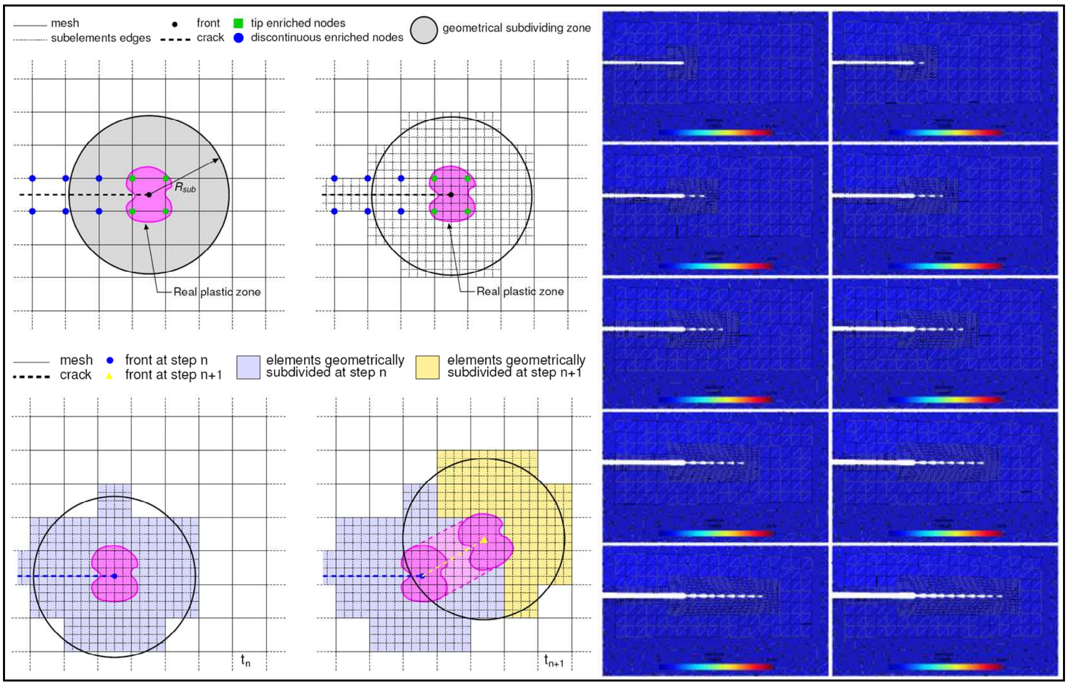



*Figure 5: Crack propagation with XFEM*

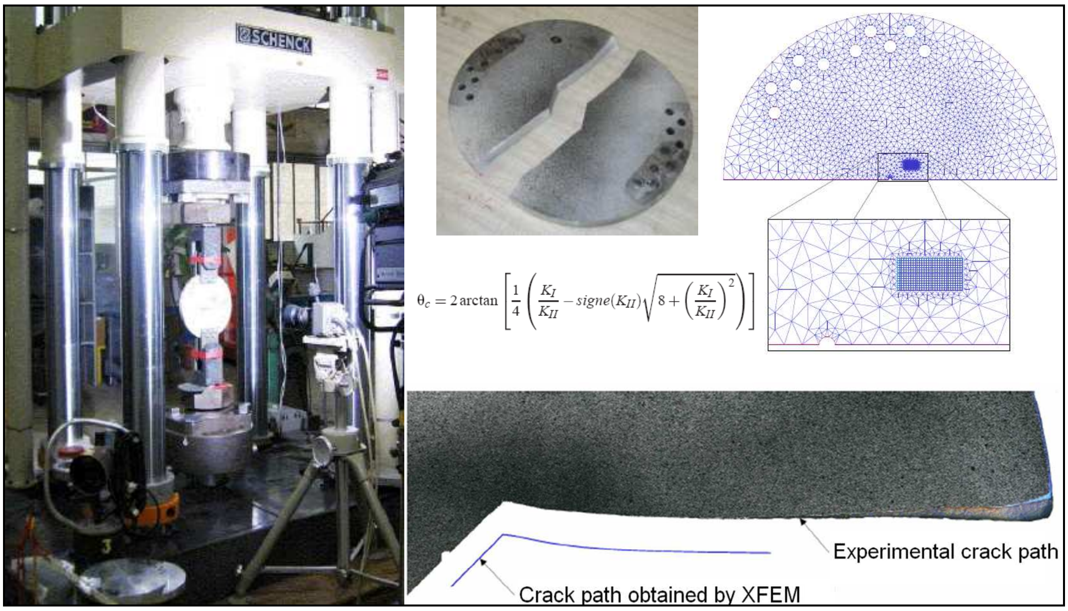



*Figure 6: Mixed mode fatigue crack growth*

References :

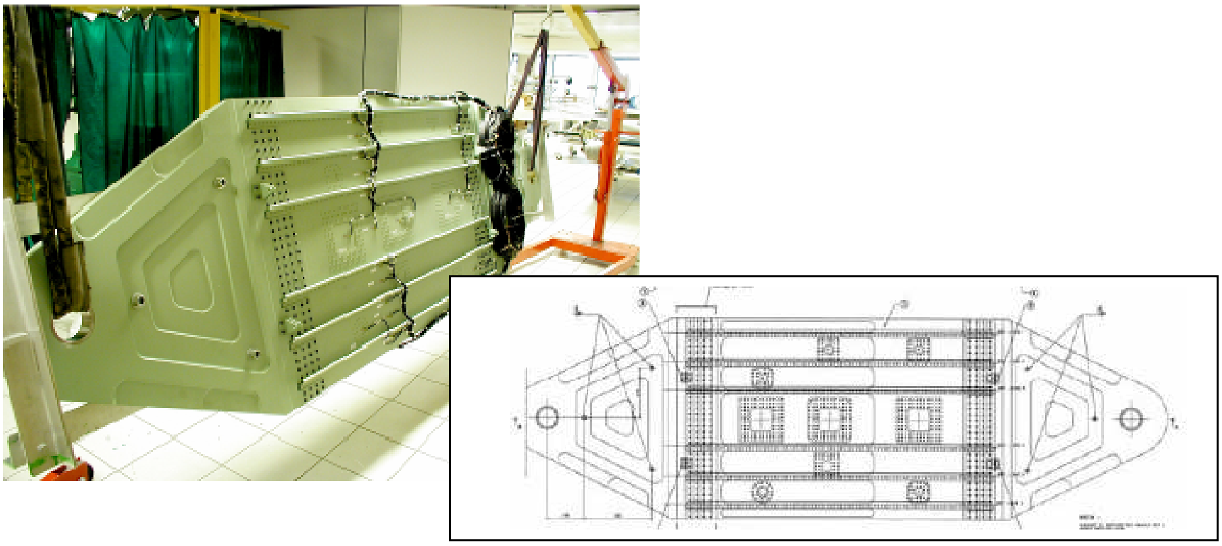
1. Pan J, Shih CF. Elastic-plastic analysis of combined mode I, II and III crack-tip fields nder small-scale yielding conditions, *IJSS* 1992;**29**(22):2795–2814.
2. Elguedj T, Gravouil A, Combescure A. Appropriate extended functions for X-FEM simulation of plastic fracture mechanics. *CMAME*, 2006;**195** : 501–515.
3. Elber W. Fatigue crack closure under cyclic tension. *Engineering Fracture Mechanics* 1970; **2**:37–45.

## 6.3. EXPERIMENTAL TECHNIQUES

### 6.3.1. Testing of structure representative coupons (EADS IW)

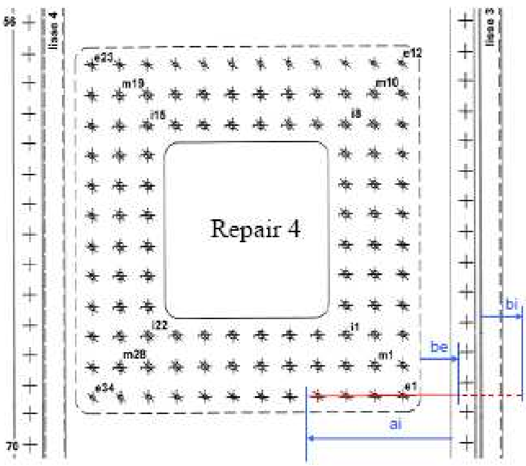
This activity was mainly carried out in the frame of IARCAS Project [1] in support to Airbus. The objective was to validate fatigue predictions made by Airbus, following Airbus / EADS IW modelling and testing work on elementary lab coupons. The fatigue issues which were dealt with are riveted skin repairs, welded stringer repairs, dents.

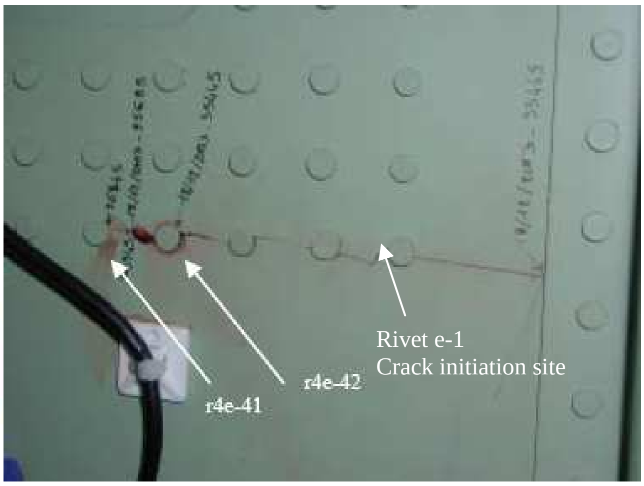
Concerning fatigue of skin repairs, a flat panel (named FFP1) with riveted stringers and skin repairs was designed and manufactured by Airbus. It has been tested by EADS IW in order to obtain data on crack initiation time and crack propagation scenario in riveted skin repairs. FFP1panel has 9 repairs: 6 two-fastener row repairs, 3 three-fastener row repairs. There are standard repairs with square corners and improved repairs with round corners or circular rivet rows. The panel has undergone 250000 full cycles (5x1.25x DSG).



Airbus made fatigue life predictions of repairs using FE analysis and a multiaxial fatigue criterion. The observed cracks initiation sites were in the corner area of repairs. The results have allowed Airbus to confirm or improve the predictions.

An example of crack initiation and growth in a standard repair with three rivet rows is shown below. The applied load is along the stringers direction. Crack initiation took place at rivet e-1 (outer row bottom right corner rivet). The crack grew towards the neighbouring stringer and rivets.



Additional details may be found in the paper prepared and presented by Airbus in the 24th ICAF Symposium.

Concerning fatigue of repairs of welded stringers and dents, a flat panel (named FFP2) with welded stringers and dents was designed and manufactured by Airbus. It has been tested by EADS IW in order to obtain data on crack initiation time in repairs and dents. Preliminary joint work between Airbus and EADS IW has allowed Airbus to define repairs of welded stringers and dents for FFP2.

FFP2 panel has 7 welded stringers and dents which are located in mid bays or close to the stringers, as shown on the figure. The skin and stringers are made out of 6056T78 alloy. The stringer repairs consist of a doubler which is riveted onto the former stringer which has been cut over a certain length of the web. The repairs differ in doubler length, stringer cut angle, presence of a stringer step after stringer cut out, number of rivets to tie the doubler onto the stringer web. A set of 16 dents was made, with different values of depth, indenter size (and energy).

FFP2 panel underwent 375000 full cycles (5x1.25x DSG). The predictions of the fatigue life of repairs and dents made by Airbus, were in line with the experimental data.

References :

1. IARCAS project "Improve and Assess Repair Capability of Aircraft Structures". Growth Project GRD1-2000-25182, 5th Framework Programme of the CEC

## 6.4. NON DESTRUCTIVE TESTING AND STRUCTURE HEALTH MONITORING

### 6.4.1. Structure Health Monitoring (EADS IW)

EADS is involved in a number of developments regarding the direct or indirect monitoring of cracks and crack growth in aeronautical structures. These developments are part of a global Structural Health Monitoring approach, with expected benefits on several levels: maintenance costs (part of the Direct Operating Costs), aircraft operability, and possibly design (especially related to damage tolerance philosophy).

Several technologies for in-service monitoring (sensors permanently bonded on the structural parts) are being looked at :

- Crack wires able to monitor extended structural elements, with possible wireless interrogation.
- Foil eddy current sensors, which are an in-situ alternative to conventional eddy current testing sensors and allow crack growth monitoring in addition to crack detection.
- CVM (comparative vacuum monitoring) sensors which also give local indications of crack presence.
- Acousto-ultrasonic sensors, laid out in a specific pattern on a structural area, which emit and receive ultrasonic waves, can indirectly detect cracks or other damages in a global manner

Lab experiments are carried out for assessing sensor performance and sensor durability in combined fatigue/environmental conditions. Sensors are also implemented on full scale structures, either taking advantage of full scale fatigue test cells, or even on flying aircraft. System issues, such as wiring integration, monitoring unit design, signal compression for easy sensor interrogation are also investigated.

As an illustration, the following result is shown (figure 1). It relates to crack monitoring on a painted stiffened plate, where fatigue loading and temperature were combined (tests at room temperature, -55°C and +80°C). The dependence of the eddy current testing sensor output signal to the crack length is clearly apparent in the graph. The picture also shows a crack wire sensor applied on a nearby location.

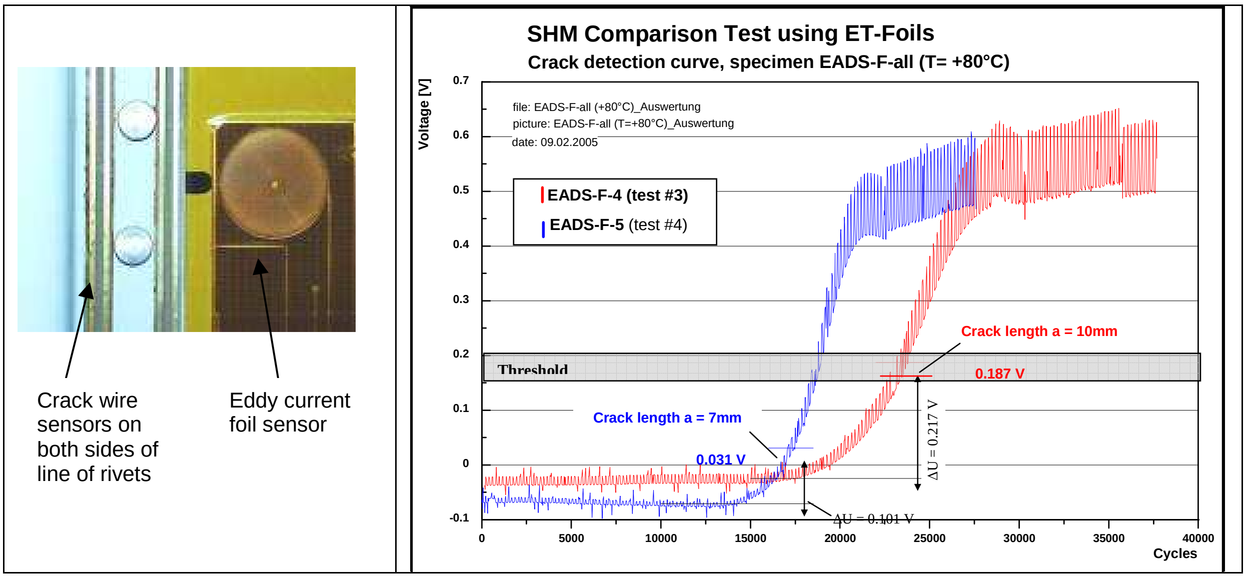



*Figure 1 : left=sensor location close to crack initiation site, right=sensor output signal as a function of cycle number*

## 6.5. FULL-SCALE FATIGUE TESTS

### 6.5.1. Fatigue test and life extension programme of the Alpha Jet (Dassault-Aviation and CEAT)

The Alpha Jet has been in service with the French Air Force since 1979. It is used mainly as an advanced trainer aircraft, and also by the FAF aerobatics team, the Patrouille de France. With aircraft belonging to the Belgian Defence, a combined total of about 180 Alphajet fly more than 30 000 hours per year, most of them in Tours and Cazaux.

During the development phase, a first fatigue test of the wing box and central fuselage had cleared a safe life characterized by a “Fatigue Index” of 180. It meant that the test had, with a scatter factor of 3, simulated 54 000 flight hours under the design load spectrum. But as often happens, it appeared quickly that the in-service spectrum was more severe than the design spectrum, and moreover, it had to be anticipated that the service life would have to be stretched beyond 2015. A life extension programme was then launched in 1993. Operational loads had previously been measured during a dedicated flight test campaign involving 3 different aircraft, and a second (this time full-scale) fatigue test was installed, operated in Toulouse by CEAT and Dassault Aviation.

Now entering its final phase, the test has yielded a considerable amount of data about the structure of the Alpha Jet. Damage areas, most of them of little structural significance, but some of them in critical components, have been revealed and the associated maintenance procedures have been validated and published :

- repairs, either preventive or curative,
- NDI methods, with their associated time of first inspection and periodicities.

Basically, the fuselage has been cleared for a safe life of 280 FI.

For wings this level cannot be demonstrated in safe life philosophy, so a damage tolerance study will be performed to clear them up to 245 FI. Observing that the wing ages at a slower rate than the fuselage, these two figures should satisfy the requirement of the user Air Forces.


### 6.5.2. Fatigue test and validation of Super-Etendard for 6,500 flight hours (Dassault-Aviation and CEAT)

The Super Etendard Marine aircraft is planned to remain in service until 2015 and is being upgraded to a new standard. Therefore it was requested to validate its use for a total of 6,500 flight hours.

As the fleet is not fitted with g-counters, the in-service spectrum was derived from an OLM (Operational Loads Measurement) campaign on two sample aircraft. The operational use of the fleet is supposed to be homogeneous with the recordings.

A fatigue test has been performed at CEAT, using two Etendard fuselages and several Etendard wings, which are very similar to the ones of the Super Etendard. A total of 34,014 flight hours have been simulated.

Fatigue cracks and corrosion in service required that several structural repairs be implemented, which were also tested.

A tear down of one of the tested wings has been initiated, to further strengthen the justification of a limit life of 6,500 flight hours.

### 6.5.3. M2000 Full Scale Fatigue Test (Dassault-Aviation and CEAT)

A full-scale fatigue test is being carried out in the CEAT Test Plant on an aged airframe (fuselage, LH wing, RH wing and vertical fin taken from several aircraft in service in the French Air Force). The test loading system is composed of 82 hydraulic jacks + 4 Fuel Tank Pressures + 1 Cockpit Pressure.

The fatigue spectrum simulates the future Fatigue Index (FI) Consumption Rate of the key elements of the structure (especially attachment areas of the wing, external stores and landing gears). It is based on the following data:

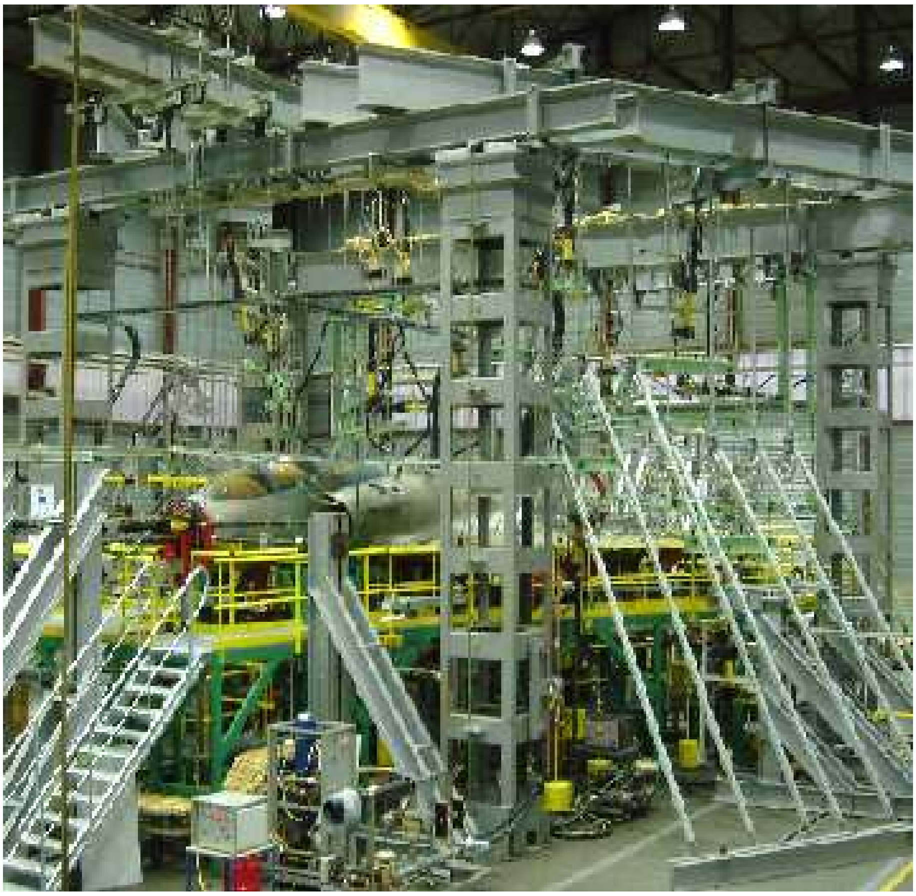
- French Fleet FI Consumption rates depending on Squadron / Version / Mission / External Store Configuration conditions,
- Hypotheses in terms of French aircraft future use (Selection of 80 Missions / External Storage Configurations, with their scheduled distribution in terms of Flight Hours)
- Updated in-flight loads (from load survey during a dedicated flight test campaign) and Ground Loads.

The test started in December 2005. The objective is to reach a Fatigue Index of 930 to demonstrate 310 FI for the safe life of the aircraft. In March 2007, the fuselage reached a FI of 477 and the wing a FI of 400.

The results of this 2nd Full Scale Fatigue Test will be :

- An important extension of the life validated by test (+ 55 %) in a "Safe Life" approach with punctual damage tolerance,
- Maintenance solutions with an improved cost effectiveness :
  - Inspection Plan Up-dating,
  - Repair Solutions validated,

- Preventive Operations defined.



### 6.5.4. Fatigue and damage tolerance certification tests of the FALCON 7X (Dassault Aviation and CEAT)

The new Dassault Aviation three-engines powered business jet named Falcon 7X is designed to fly 5,950 nm with eight passengers plus a crew composed of three pilots and a flight attendant, operating at a maximum speed of 0.90 Mach. Its wing span of 25 m is comparable to the one of the Falcon 900EX, but the aircraft is somewhat longer (22 m against 20 m). It will be the first fly-by-wire business jet, conferring precise flight path control, automatic trim adjustments during configuration changes and basic autopilot functions through the cockpit side-stick controller for setting heading and attitude. In addition, the Falcon 7X engineering leveraged the use of Dassault Systems CATIA software as the foundation to create complete virtual definitions of the aircraft and ensure a living representation of the aircraft from concept through production.

Both static strength and fatigue/damage tolerance substantiation is carried out on a unique full-scale test article. Under a Dassault Aviation contract, CEAT has carried out the test rig engineering composed of 64 hydraulic jacks + fuselage pressurisation, and around 2000 measurements (strain gauges and displacement sensors). The fuselage and wings of the airframe were received at CEAT end of November 2004 as planned months before. The assembling of the test fixture started in June 2004 and preliminary static tests began only two months and a half after airframe assembling by Dassault staff. A first sequence of 50,000 flights representing two aircraft lives was simulated at CEAT's premises between May 2005 and April 2006. Then several static cases were applied to the structure (5 at limit loads and 5 at ultimate loads). Before entering the damage tolerance phase, 80 artificial damages were created in some critical locations. Cycling for the damage tolerance phase started in November 2006 for another lifetime. Test is still running and currently about half an aircraft life (10,000 flights) has been simulated.

### 6.5.5. Transall structure life extension (AIRBUS & CEAT)

Developed in the 60's in a French-German co-operation, the TRANSALL C160 aircraft is a military transport aircraft. 67 of them are used by the French Air Force for tactical and humanitarian missions, basically. The service life extension for the Transall from 20,000 to 22,500 Flight Cycles, corresponding to 5 more years in service, was decided in 1996 for the following major reasons:

- the advanced fleet age of aircraft in service,
- the estimated date of entry into service of the new generation military aircraft.

The definition and substantiation of the life extension programme have been based on the analysis of both :

- an extensive in-service damage collection with the establishment of a damage data bank,
- a full scale fatigue test on an aircraft retired from service.

The major participants in this process were: A.I.A (Atelier Industriel de l'Armement) from "Clermont-Ferrand", CEAT, SPAé (Service des Programmes Aéronautiques) and AIRBUS.

A big concern was to define the load spectrum to be applied to the test airframe. A usage monitoring campaign was launched in 1996 for this purpose based on:

- collection of general information about each flight of each TRANSALL aircraft (paper form containing the type of mission, flight duration, take-off and landing weights, door openings for droppings…),
- in-flight recording of flight parameters and stresses on 4 aircraft of the fleet, to derive the loads associated with each type of mission.

A large amount of data have been collected over 3 years, exchanged by the different partners of the programme and analysed.

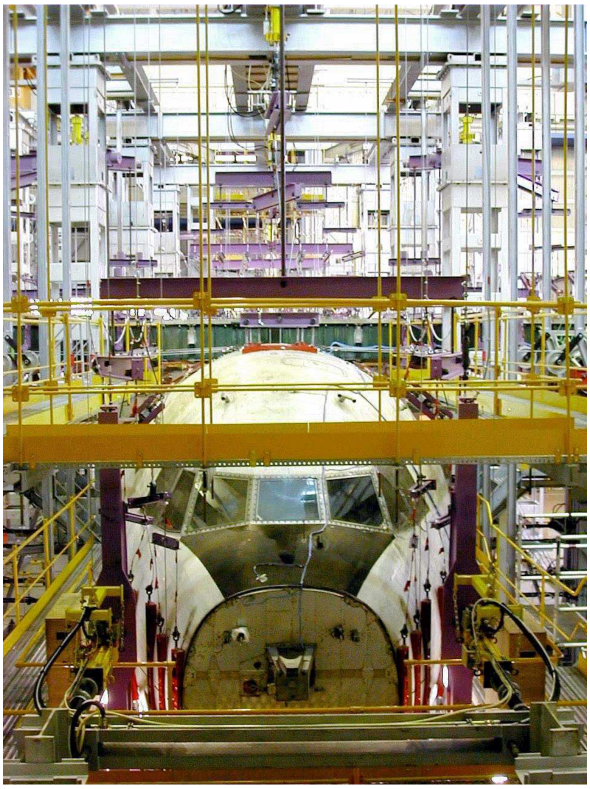
At the same time, the assembly of the test fixture at CEAT was completed. It consists of 112 hydraulic jacks + fuselage pressurisation, and around 600 strain gauges.

After a few last adjustments, the test began in November 1999.

First major damages, which appeared on the lower wing panels around man holes, have already induced a specific maintenance programme for the fleet. Some additional coupon tests on specific details were performed to evaluate the more adequate preventive modification solution. New major damages appeared in October 2002 on the lower wing panels and concerned doublers around fuel pumps (cf ICAF 2003 French National Review). In November 2003, further new major damages (cf ICAF 2005 French National Review) were encountered after 34,000 simulated flights on panels inner surfaces of the centre wing box leading to eleven months of complete stop of cycling. Investigations, including fractographic analysis have been carried out to deduce repercussions for the fleet.

In March 2006, during an inspection at 44,750 flight cycles, new major damages were discovered at rib #1560 especially in the rear spar of the centre wing box leading to stop the test again. After analysis, AIA has designed a repair which is currently applied on the structure. Due to the complexity of this repair, test is not expected to start again before summer 2007.

On the basis of 44,750 flight cycles completed, Airbus has calculated that, in the most critical areas which are the centre wing box inner panels, 18,057 flights (landings) have been substantiated corresponding to 22,390 flight hours.



## 6.6. IN-SERVICE AIRCRAFT FATIGUE MONITORING

### 6.6.1. System General Description and Data Collection (CEAT)

Military French fleets are monitored trough 3 different systems:

- A basic unidimensional system for most of the fleets, based on records of vertical load factor exceedences with g-counters.
- A multichannel system (5 analogic channels + 7 binary parameters data), named MICROSPEES, for Mirage 2000D fleet, which gives an improved three-dimensional approach through g-meters, without any strain gauge.
- A more sophisticated system named HARPAGON for Rafale fleet which includes a structural fatigue monitoring based on the same approach as MICROSPEES but with much more parameters recorded (30) et structural points tracked (43). The whole computing system has been validated now and first fatigue calculations were recently

performed for the Rafale. These results participated in the monitoring of the operational activity of the fleet.

All these systems have been described in details in previous French National Reviews.

### 6.6.2. Improvement and Renovation of Fatigue Computation and Data Collection Tools (CEAT)

Most of the tools used in fatigue monitoring are evolving so as to minimize the constraints for users and improve the quality of monitoring.

*Data collection for g-counters: SARA.*

A software, named SARA, has been developed to be used in squadrons for computational fatigue data collection in replacement of the debriefing forms manually filled in after each flight. This tool aims at bringing more efficiency for users in collection and a better quality level of the basic data for fatigue calculation.

It is about to be installed on every squadron concerned.

*Fatigue computation system for g-counters approach: PEGASE.*

The global computation system is being renewed, using the same calculation models, in order to adapt means of calculation to modern computing abilities. The objectives of this evolution are :

- More ergonomy and efficiency for the software
- More aspects of the aircraft lives taken into account (inspections, reparations…)
- More analysis tools to enable an accurate use of fatigue results

*Data collection for MICROSPEES: ARCADE.*

Once validated, ARCADE will be deployed in M2000D French squadrons to correct and improve the data pre-treatment and guaranties a maximal accuracy of the records used for fatigue computation by MICROSPEES system.

### 6.6.3. Reprocessing of M2000 individual fatigue data (Dassault-Aviation and CEAT)

The Mirage 2000 usage scheduled by the French Air Force pointed out the need to extend the fatigue life, waiting for a large deployment of the Rafale. As the oldest aircraft were reaching the limit Fatigue Indexes (FI) demonstrated by the first full-scale test, it has been decided to study the damaging speed of the aircraft. More details about this problematic are given in the previous French National Review.

In this context, Dassault-Aviation launched a re-evaluation of the aerodynamic data base of the aircraft. This renewal was based on more accurate aerodynamic numerical codes developed for the Rafale and supported by a whole flight test campaign led on M2000 equipped with calibrated strain gauges. These results implied a re-estimation of load calculations for the fleet, including :

- an increase of the fuselage lift efficiency,
- a variation of the centre of lift position,
- a validation of non linear behaviour in high pitch attitude.

It appeared that the stress to load relationships were overestimated in fatigue computation and that a re-evaluation of these ones could lead to a more accurate calculation and a global gain of potential for the whole fleet.

Dassault Aviation established these new relationships, so that CEAT could perform a global reprocessing of all the individual recorded fatigue data of M2000 fleet, that's to say the data :

- of all the aircraft,
- from all the versions,
- on all the tracked points,
- for all the years since the entry in service in 1983.

After validation of the relations and reprocessing results, this treatment delivered a global gain on the whole fleet remaining potential of more than 10%, which contributed to Mirage 2000 life extension, in parallel to a new full-scale fatigue test which is currently in progress at CEAT.