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REVIEW OF AERONAUTICAL FATIGUE INVESTIGATIONS

IN FRANCE DURING THE PERIOD MAY 2003 - APRIL 2005

Compiled by

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INTRODUCTION AND ACKNOWLEDGEMENTS

The present review, prepared for the purpose of the 29th ICAF conference to be held in Hamburg (Germany), on 6-7 June 2005, summarises works performed in France in the field of aeronautical fatigue, over the period May 2003-April 2005.
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 :

- MM Franck Gallerneau for ONERA,
- Mr Lionel Le Tellier for Dassault Aviation,
- Mr MarcBalzano for Airbus France,
- MM Bertrand Journet and Didier Simonet for EADS, Joint Research Center (CCR),
- MM Alexandre Lahousse and Jean-Philippe Gallard 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.

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6.1 FATIGUE LIFE PREDICTION STUDIES AND FRACTURE MECHANICS

6.1.1 Extension of a crack growth model with fatigue-creep-environment interaction to non isothermal loading (ONERA)

The extension of a crack growth model [1] to high temperature complex loading and for its application to typical loading generated in a turbine disc, is proposed. The model is based on an extensive experimental study performed by SNECMA on N18 from 450ºC to 650ºC, in isothermal and also in non isothermal condition, which comprises fatigue with or without hold times and special sequence tests representative of the disc in service. The crack growth model is built up in the framework of classical linear elastic fracture mechanics. Time effects at high temperature are traduced by creep-fatigue and oxidation-fatigue interactions. The proposed writing in non-isothermal condition [2] is very attractive for easy model identification on a large temperature domain. Model predictions are fairly good for a large set of experimental data including complex loading in non isothermal condition, as shown in figure 1. The use of this model, with a better understanding and modelling of physical phenomena, should allow to limit the conservatism required for lifetime prediction, and thus to give to the users a better use of the real potential of the components while maintaining a high security level.

[1] Kruch, S., Prigent, P. and Chaboche, J.-L., *Int. J. Pres. Ves. & Piping*, Vol. 59, 1994.
[2] Gallerneau F., Kruch S., Kanouté P., Burgardt B., ”A new modelling of crack propagation with fatigue-creep-oxidation interaction under non-isothermal loading”, AVT Autumn 2001 and Panel Business Week on Ageing Mechanisms and Control, Manchester, 8-12 October 2001.

6.1.2. Scale and gradients effects (EADS CCR)

The prediction of fatigue crack initiation is commonly achieved through the use of multiaxial criteria. Although numerous criteria exist in the literature, the stress gradient effect or the well known difference, which is observed in metallic materials, between traction and bending fatigue experiments, still remains difficult to predict and thus limits the use of these criteria for the analysis of structures with stress concentrations.
Research work has started with the objective to review the formulation of some criteria, to propose and validate an approach that will alleviate these limitations. The work has focussed on the definition of a critical volume in which micro cracks develop and lead to crack initiation. Then the criterion has averaged over this volume. The predictive capabilities of the approach has been evaluated by computing Haigh’s diagram for several kinds of loadings and stress gradients, and confronting the results with experimental data. The qualitative behaviour is promising according to the first comparisons between experiments and calculations.
[3] C. Schwob, F. Ronde-Oustau, L. Chambon, *Fatigue crack initiation in stress concentrating areas*. To be presented at ICF 16.

6.1.3 Effects of dents (EADS CCR)

Dents on fuselage stand with some residual stresses due to the incident that caused them with plastic deformation and spring-back effect. The current justification methods for dents in fatigue and damage tolerance do not take into account the residual stresses. Within the framework of a IARCAS project, a predictive approach has been developed using finite element analysis in collaboration with AIRBUS-F:

- Step 1 : simulation of the denting process using elastoplastic FE calculation using shell elements (this generates the residual stress field).
- Step 2a : fatigue analysis. Application of the service loads on the model which contains the residual stress field (from step 1) and computation of a multiaxial fatigue criterion to predict the fatigue life.
- Step 2b : damage tolerance analysis. A through crack is introduced into the model which contains the residual stress field (from step 1), application of the service loads and calculation of the elastic stress intensity factor at each crack tip. Then the prediction of the fatigue crack growth rate is made using the baseline $da/dN-\Delta K$ equation of the alloy.

The approach has been applied to rectangular coupons made out of 6056T78 alloy, 1.2 mm thick, each with one dent, as shown figure 2.
Step 1 was validated by comparing the calculated and experimental applied force and achieved dent depth, see figures 3 and 4.
Concerning the fatigue analysis (step 2a), coupons with dent depth values of 5, 7 and 10 mm (indenter radius of 50 mm) have been fatigue tested and calculated. The graph figure 5 shows that the fatigue predictions fall mainly within a scatterband of 2 with the test data.
Concerning the damage tolerance analysis, the stress intensity factor was calculated at each crack tip at three locations within the thickness of the sheet : upper skin, mid thickness, lower skin, see figure 6.
Both graphs figure 7 shows that the predictions using the stress intensity factor calculated at mid thickness compares fairly well to the experimental data.

[4] IARCAS project "Improve and Assess Repair Capability of Aircraft Structures". Growth Project GRD1-2000-25182, 5th Framework Programme of the CEC.
[5] B. Journet, F. Congourdeau, C. Ithurralde, S. Bouissou and C. Meyer, *Damage Tolerance of Fuselage Dents*. To be presented at ICAF 2005.

6.1.4 Spectrum loading (EADS CCR)

PREFFAS model is used in AIRBUS-F for the damage tolerance analysis of fuselage parts. This model has been developed within EADS (actually in former AEROSPATIALE CCR, the Joint Research Centre). This model makes a spectrum analysis to calculate the crack growth retardation effect. Three parameters need to be identified in order to perform the crack growth calculations : two related to Paris' law and one for the retardation effect. Two tests are thus enough for their determination : a constant amplitude loading (CAL) 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.
Due to the introduction of the welding technology, PREFFAS model has been tested on coupons made out of 6056 alloy, 3.2 mm thin, with a laser beam butt joint weld in the middle. The two baseline tests were run plus one under spectrum loading (A330 fuselage).
The results figure 8 show that the model fairly well predicts the crack growth behaviour under spectrum loading (within 5% when the crack remains below the high crack growth rate regime, in which K is in the vicinity of Kc). Several predictions were made because the identification of the retardation coefficient was not straightforward since the two baseline tests did not yield parallel lines. Further on, it is recommended to run a periodic overload test with a lower overload ratio, for instance 1.4 instead of 1.7, because of the sheet thickness.

6.1.5 R curve extrapolation (EADS CCR)

EADS CCR has developed an approach to simulate the residual strength of coupons (R curves) or that of stiffened panels. The approach is based on an 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.
During the last two years, the method has been used for two purposes : extrapolation of R curve and review of the ASTM validity criterion.
The application of the R curve method to assess the allowable cracks usually suffers from a too limited validity range. There is a need to dispose of R curves obtained on large coupons or to make the validity criterion less severe. The simulation can save testing and material cost since it can predict large R curves from a single test on a small coupon. This has been proved on 6056 alloy, predicting results on a CCT specimen with W=760mm from a CCT W=400mm R curve [6].
Figure 9 shows, on a 2024 alloy, simulated R curves from W=160 mm to W=1500 mm. Then one can use the R curve of the necessary size.
Another exploitation of these curves is to try and relieve somehow the ASTM validity criterion. The same figure shows how that on W=400 mm can be raised: comparing simulated curves between W400 "non valid data points" and W760 "valid data points", when the two curves are within 1%, the non valid data points can thus be considered as valid. On the 2024 alloy, the simulation shows that the validity domain can be increased up to 60 %, depending on the specimen width. Therefore valid test data show an extended valid domain that can suit the targeted analysis.
[6] IDA project "Investigation on Damage Tolerance Behaviour of Aluminium Alloys". Growth Project GRD1-2001-40120, 5th Framework Programme of the CEC.

6.1.6 Fatigue fretting (EADS CCR)

Fretting is a significant source of damage primarily in the rotating parts of helicopters (gearbox and rotor hub specifically), translating into higher maintenance cost and/or in-service incidents. Although fretting damage can be contained by using palliatives (with much engineering judgement involved), a better understanding of the fretting damage process is needed to assess the sensitivity to fretting during the design phase. Following a long lasting research effort in the field of contact mechanics, EADS CCR investigated the ability of the notch-analogue concept, pioneered by Prof. Suresh's group at MIT, to account for the effect of the loading parameters (normal and tangential forces) on the fretting fatigue life of laboratory specimens (sphere-on-flat contact) [7].
It appeared that considering the contact problem as an extremely severe stress concentration, i.e. as severe as a crack, provided, in combination with simple fracture mechanics concepts and using only independently derived parameters, good qualitative and quantitative estimates of the effect of the loads on the fretting fatigue life, as illustrated figure 10. The solid line represents the predicted lives, whereas the crosses are experimental data points, obtained by varying the normal force for a fixed tangential force (experimental results from [8]).

[7] L. Chambon, B. Journet, *Modelling of Fretting-Fatigue in a Fracture Mechanics Framework*. Presented at ISFF4, 4th International Symposium on Fretting Fatigue, Lyon, France, may 2004.
[8] B. P. Conner, *Mechanical and microstructural effects on fretting fatigue of Ti-6Al-4V*, Master's thesis, MIT, May 2000.

6.1.7 Evaluation of a numerical criterium to predict fretting-fatigue crack initiation (CEAT)

A numerical study has been performed by the CEAT (Toulouse Aeronautical Test Center) to evaluate a combined experimental-numerical criterion to assess fretting-fatigue initiation. In their paper, Lykins, Mall and Jain propose that the fretting initiation time can be evaluated with a shear stress range critical plane approach, provided that the shear range parameter is fitted on an experimental S-N curve obtained with a friction pads experimental apparatus.
On the basis of such previous tests, CEAT has carried out a numerical modelling of the friction pads tests (figure 11) and some good correlation were found between the observed initiation site and the location of the criterion maximum value. Some others phenomena have been predicted such as the fact that the initiation occurs not exactly on the surface but at little depth under the surface. This phenomenon is well-known in the rails abrasion.
To confirm the predictive capability of this criterion, CEAT has built from the basic experimental S-N curves a master S-N curve expressed relatively to the shear stress range parameter. This curve has then been applied to predict the fretting-fatigue lifetime of a wing-fuselage junction under a complex spectrum cycling. A whole wing spar and the corresponding frame lug have been modelled (figure 12) and the shear stress range criterion has been computed. Then a classical spectrum analysis via a Rainflow calculation and a linear cumulative damage law has been performed but on the basis of the master S-N curve previously built. The prediction results have then been compared to experimental results of a wing-spar fatigue test under complex cycling. Good agreements were found both an the location of the initiation site (figure 13) and between the estimated and observed lifetimes.

6.1.8 Enhancement of metallic structures fatigue and damage modelling – Corner crack growth (CEAT)

A study has been carried out by the Toulouse Aeronautical Test Centre (CEAT) in the scope of a R&T programme named "Conception and structural strength control of fighter aircraft airframes", as a support to works of Dassault Aviation company. Two major topics of this R&T programme are : "Enhancement of metallic structures fatigue and damage modelling" and "Corner cracks growth".
The first topic deals with the residual strength of cracked structures in order to enhance the design criteria for given materials and spectra, which match with French fighter applications. To achieve this goal, a specific coupon with a double recess, called "Bialveole", (figure 14) has been defined and tested. Its geometry was such that a 200 mm wide specimen shows the same Strength Intensity Factor as a CCT 1200 and thus allows to simulate a R-Curve test with a larger validity range. Furthermore, CT and CCT coupons have been tested to control Bialveoles results.
After a first phase consisting in a fatigue crack growth under constant amplitude or complex spectra, the main objective of the tests was to measure the residual strengths of the coupons. Three predefined load steps and then a loading up to failure were applied to the specimens. The tearing was controlled with the electrical potential method of CEAT during the tests and after with a specific coloration method developed at CEAT too. The second method allows to measure the stable tearing for each load level thanks to an image analysis software (figure 15).
Classical processing of tests data gave crack growth curves and tearing as a function of load (figure 16). In addition, to that, stable tearing for each load level was also measured with the coloration method. As the main fields of interest were to evaluate the Bialveole concept and the residual strength approach, a R-Curve data processing (figure 17) was also applied to CCT and Bialveoles test results. R-Curves built with this process allowed to validate the Bialveole concept, and showed a good correlation in the early part with CCT.
The second topic deals with corner crack growth. It consisted in performing several fatigue tests on 2024 T351 aluminium square specimen with two corner machined cracks in order to better estimate the damage growth and static failures of this type of cracks commonly met on fighter aircraft thick elements.
If the growth of through cracks is well known and quite predictable today, it is not the same for the growth of corner cracks whose evolution to through crack is not directly quantifiable and leads to a conservative approach when determining the inspection intervals.
Indeed, the growth and static tearing of corner crack have the particularity to increase faster in the core of the material than on free borders. This is particularly concerning for control methods which are generally based on the crack length on surface.
Fatigue tests results allowed to show the quasi-elliptical forms of crack fronts by coloration of them and to apprehend the borders effect. The growth of corner cracks was realised with a four-point bending of the specimen under constant amplitude and complex fatigue spectra (figure 18).
Tests also permitted to characterise, thanks to coloration process, the fronts' evolution and shapes after stable tearing for imposed static load steps (figure 19 et 20). An experimental method was developed by the CEAT to optimise those static load steps.
Tearing forms show clearly different stress conditions along the front, i.e. mainly plane stresses on free borders, mainly plane strains in the core of the material and intermediate stresses between states.

To develop the numerical fatigue tools, a correlation was realised between tests results and numerical fatigue predictive computations. Computations of stress intensity factors (SIF) were performed using the finite element software SAMCEF which permitted to implement a geometrical model in the NASGRO software (figure 21).

6.2 COMPUTATIONAL TECHNIQUES

6.2.1 Residual strength of welded stiffened panels (EADS CCR)

Fatigue and damage tolerance methods developed by EADS CCR have been implemented to carry out a design study of stiffened panels with respect to the residual strength. Examples of application of the approach to predict the residual strength of welded stiffened panels were presented at ICAF 2003 [9].
The design study was manifold. Running the simulation on stiffened panels has allowed the following investigation :
- Influence of stringer shape (head, web, foot) on best trade-off between weight and residual strength.
- Compare different alloys for the same stringer shape with respect to residual strength.
- Influence of the initial crack length and crack tip location (with respect to stringer foot) on the residual strength.

Having an initial crack tip already in the thicker area of the stringer foot may result in a 15% loss of residual strength. Furthermore the simulation can help understand the disymetric propagation of the crack (figure 22).
[9] F. Congourdeau, B. Journet and C. Meyer, *Damage Tolerance of Fuselage welded Stiffened Panels*. Fatigue of Aeronautical Structures as an Engineering Challenge, Proceedings of the 22nd Symposium of the International Committee on Aeronautical Fatigue, ICAF 2003, Lucerne, Switzerland, 7-9 may 2003.

6.2.2 Tools integration (EADS CRC)

CRACK-KIT® (www.eads.net/crack-kit or crack-kit@eads.net)
EADS CCR in-house BEM based code has been concerned with new developments such as taking into account residual stresses to calculate fracture mechanics parameters, using superposition. The residual stress field is imported from a finite element analysis, and superposition is invoked to calculate the stresses and displacements in the structure after introduction of a crack and a linear redistribution of stresses. A screen shot of CRACK-KIT showing the residual stress field at a notch is shown figure 23 to illustrate this procedure.
The crack opening is used to derive fracture mechanics parameters. The reduction of stress intensity factor expected from compressive residual stresses (e.g. due to cold working) has been demonstrated. More qualitative correlations, using notched specimens loaded before fatigue to introduce residual stresses, show that the magnitude of the residual strength reduction is well predicted (within about 10%) by this simplified method.

6.2.3 Improvement of fatigue assessment of riveted and bolted metallic joints (Airbus France)

The riveted and bolted metallic joints remain the most critical areas in fatigue. Furthermore, it is often requested in the new Airbus programmes to optimise the primary structure in term of weight.
As a consequence, additional efforts have been done in order to improve the fatigue assessment of such a type of structural detail:
- improvement of the local stresses calculation (stress concentration effects) using adapted FE models as a function of the geometry. These different types of models are easily accessible inside a library included in a ergonomic application and they are validated thanks to realistic specimens tested under cycling loading,
- better integration of all the technological processes using a relevant strategy of tests (different standard coupons) to quantify:
    . the effect of fastener types (solid rivets, blinds rivets, screw bolts, swaged bolts),
    . the effect of hole tolerances (clearance, transition, interference fits),
    . the effect of cold working (standard, Busloc, Forcemate,…),
- better understanding of the spectrum effects using appropriate laws to deduce the fatigue life of joints.

All these improvements combined with the experience coming from either the analyses of full-scale fatigue test damages or in-service damages allowed to get a high level of reliability for the design of such structures.
All this is illustrated figure 24.

6.2.4 Extended Finite Element method for crack modelling (Airbus France)

In the Finite Element Method (FEM), a partition of domain into sub-domains (elements) forms the basis of mesh generation. The presence of flaws or in-homogeneities such as crack, void and inclusion must be taken into account in mesh generation through a perfect conformity of mesh with these geometrical entities.
The extended finite element method (XFEM) alleviates much of the burden associated with mesh generation by not requiring the Finite Element mesh to conform to cracks. The essence of XFEM lies in sub-dividing a model problem into two distinct parts : mesh generation for the geometric domain (cracks not included), and enrichment of dedicated elements of the Finite Element model by additional functions that model the flaw(s).

In the classical Finite Element Method, the displacement field in the element is derived from the nodal displacement according to the following equation, N being the shape function :

$$\mathbf{u}(x,y)=\sum_{i=1}^{n}N_i(x,y)\mathbf{u}_i$$

In the XFEM method the displacement field is enriched as follows :

$$u(\mathbf{x})=\sum_{i\in N}u_iN_i(\mathbf{x})\boxed{+\sum_{i\in L}b_iN_i(\mathbf{x})H(\mathbf{x})+\sum_{i\in K_1}N_i(\mathbf{x})\left(\sum_{l=1}^{4}F_l(\mathbf{x})c_i^l\right)}$$

Supplementary degree of freedom for crack modeling

H refers as the generalized Heaviside function for the discontinuity along the crack path and F(x), dedicated functions of displacement field at crack tip.
Consequently, when applying this technique, the crack can surprisingly develop through the mesh as described in figure 25, preventing any re-meshing of the structure while propagating.
Comparison of Stress Intensity Factors with exact solution regarding degree of element, mesh refinement, method for numerical integration, etc. is on going (figures 26 through 28).

6.3 EXPERIMENTAL TECHNIQUES

6.3.1 A380 fatigue spectrum simplification for test purpose

It is first time on A380 that Airbus will perform the fatigue test on the entire aircraft, and this present a significant challenge. The fatigue loading which is to be applied has to represent the real service loading but within the limits of the test laboratory and the testing time.
To fulfill the requirements several assumptions and simplifications were done, namely grouping of the flight phases, the frequency based truncation and omission. The truncation of the rare events is important in order to limit the benefit from the crack growth retardation. The omission of small and non-damaging stresses performed with the intention of shortening the testing time. Different truncation and omission levels as well as the grouping of the flight segments were numerically simulated and the damage was calculated. With this approach it can be ensured a common omission and truncation for the whole aircraft.
To ensure the validity if these assumptions, an enhanced test validation program is carried out. Here the fatigue and crack propagation stages are addressed for a range of new and advanced materials. The tests are performed on specimens with a simple geometry as well as specimens representing some assembly features of the aircraft (figure 29).

6.4 NON DESTRUCTIVE TESTING

6.4.1 Use of eddy current sensors for fatigue crack detection and evaluation in thick assemblies (EADS CCR)

Currently there are several techniques able to detect and evaluate cracks in the assemblies during the fatigue tests. The most usual methods are obviously the ultrasonic and/or eddy currents techniques, also used in service for maintenance operations. The arrival of hybrid assemblies (CFRP/ALUMINIUM) increasingly thick and complex as well as the multiplicity of the interfaces make these controls increasingly difficult and sometimes impossible in certain configurations. One of the solutions under consideration by EADS CRC within the framework of its activities on the monitoring is the embedding of eddy current sensors with a thickness of several tens of µm, inside the assemblies interfaces. With this sensor technique, it is possible to realise complex design able to fit geometrical specificities of the inspected areas (for example to encircle a clamp hole). It is also possible to put several sensors on the same support in order to instrument a large area.
Another advantage of this technique is the possibility to monitor in real time the initiation and the propagation of the cracks. It also makes it possible to supervise, at low cost, the significant zones which are usually not inspected.
Several sensors of this type currently exist on the market, but the majority of them were only conceived to be implemented on the surface. The constraints related to the pressure due to the tightening torque and friction, make them unusable in assembly's interfaces. EADS CCR thus defined and produced a sensor able to fit specifications of pressure resistance, behaviour in temperature and durability in term of planned life cycles. The objective was to ensure a sensor lifetime longer than the structure.
Fatigue tests with a duration of two lifetimes, were carried out on double shear test samples (figure 31). A tightening torque following the ADET 0030 (1.06 m daN) was applied to screw.

The sensors have been working perfectly throughout the test period and did not show any anomaly after examination (figures 32 and 33). The next stage will be thus to implement these sensors on full-scale fatigue tests.

6.5 FULL-SCALE FATIGUE TESTS

6.5.1 - Alphajet fatigue test (Dassault Aviation & CEAT)

In service in the French Air Force (FAF) since 1979, the Alphajet training and aerobatics aircraft has been the subject, since the end of 1994, of a life extension programme with the aim to define the actions to be taken such as to continue both economical and safe operations beyond the original service life. The resulting extended life should allow to fulfil the FAF's needs beyond 2001 and up to 2016 with 150 aircraft operating about 38,000 flight hours per year.
This programme mainly relies on a durability test (figure 34) currently performed on the airframe of the first aircraft having reached the original safe life limit of 180 Fatigue Index (FI) which was substantiated at the beginning of the serial production through an initial fatigue test carried out up to 540 FI (equivalent to 54,000 hours of the expected usage). Up to now, in addition to the 180 FI experienced in service, the test airframe has accumulated 535 FI.
Should the scatter factors usually considered for French military aircraft to promulgate service lives from single full scale fatigue tests be applied, the test progress should hardly be sufficient to release a significant life extension. Nevertheless, probabilistic considerations based on in-service load monitoring have permitted to make allowance for both present and initial full scale test results and to reduce the value of the scatter factor to be used while keeping unchanged the provided safety level. With this, an increased safe life limit beyond 220 FI could be adopted.
In addition the present test has been shown very useful :
- to determine growth rates for cracks revealed by periodic inspections on the tested structure and also, in some cases, on the aircraft in service,
- to develop and/or adapt appropriate NDI methods,
- to develop repair solutions ranging from interim repair to more definitive ones, themselves either preventive or curative, and to assess the fatigue potential of the repaired structural parts.

Some fastener holes of the Alphajet aircraft wing were found to be sensitive to fatigue. Several repair and preventive methods were investigated to enhance the fatigue life of the structure. The FTI Split Sleeve cold expansion technique was considered as the most appropriate.
A study has been carried out by CEAT to evaluate the benefits in crack initiation and crack growth brought by hole expansion technique in general
-A numerical model was developed to get the tangential residual stress field nearby the fastener hole (figure 35).
-An analytical model was developed to calculate the benefits on crack initiation (see figure 3).
-The benefits on crack growth was calculated using the AFGROW software which has the facility to calculate the stress intensity factor in presence of residual stresses (figure 36)

The above method was applied to a countersink hole representative to the Alphajet aircraft wing concerned holes. The stress concentration factor and the tangential residual stress field were numerically obtained. The effect on crack initiation and crack growth were evaluated.
It was concluded that the gain in crack initiation is significant for that geometry; however, there is hardly any gain in crack growth in the concerned case.

6.5.2 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 will be 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 are: 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 (figure 37).
After a few last adjustments, the test began in November 1999. Up to now, 38,000 Flight Cycles have been simulated in addition to the Flight Cycles experienced in service.
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 (figure 38) were encountered after 34,000 simulated flights on panels inner surfaces of the central 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 order to evaluate the propagation duration and then deduce the inspection interval on the concerned area, the cracked surface has been examined. Macro-marks were found and an analytical study was carried out to correlate them with the load spectrum events (figure 39).
The most significant peaks in the spectrum sequence, able to produce those macrocracks, needed to be identified. These has been using Elber's model. The overload effect on the Effective Stress Intensity Factor ratio (ΔK_{eff}) was determined and translated into crack growth speed ratio (figure 40).
It was found that 11 peaks in the load spectrum may create macro-marks, the 11th being the most significant, possibly causing static tearing.
This evaluation allowed the determination of the growth history of the crack in the concerned area (figure 41).
Back to the whole life extension programme, tear-down inspections are expected at the end of the test to complement the fatigue test and in-service damage data, in order to establish the life extension conditions and the updated maintenance programme necessary to operate the fleet beyond 20,000 flights. Having the experience of damage detection occurrence, the potential of 20,000 flights should be substantiated beginning of 2007 and the 22,500 flights in early 2008 while the oldest military aircraft operating in the French fleet will only reach 20,000 flights mid of 2008.

6.5.3 Fatigue Tests of the Rafale landing gears (Messier Dowty & CEAT)

The first Rafale M are already in service in the French Navy and the Rafale B and C will be in operation in the French Airforce, soon. After assessment of structural resistance by full-scale ground testing of an airframe (static strength substantiation plus two simulated lives in fatigue), specific fatigue tests are being performed on the landing gears (static tests are completed).
Four different landing gears are tested : the main and the nose landing gears of the Rafale M and the main and the nose ones of the Rafale B. For each of them, a specific load spectrum, including: taking off, landing, breaking, turns, and, for the Rafale M, catapult launches and landings on aircraft carrier, are applied.
For the Rafale B qualification, 4,200 Flight cycles have to be substantiated which means that 21,000 cycles have to be simulated by full-scale laboratory tests. For the Rafale M, originally 4,900 cycles extended to 6,300 in June 2003 were to be simulated leading to the performance of 31,500 simulated cycles.
In April 2004, 24,500 Flight cycles were completed on the main and nose landing gears of the Rafale B with only minor damages.
Nevertheless for the nose landing gear of the Rafale M, a significant rupture of the shock absorber tube occurred in August 2004 after 10,500 Flight Cycles. Subsequent analysis and repair solutions are under investigation since then. For the main landing gear, 24,500 Flight Cycles have been performed up to now, corresponding to the initial potential to be demonstrated before extension.
NDT inspections are performed at given intervals, and will lead to subsequent analysis if needed.

6.5.4 Mirage 2000 life extension (Dassault Aviation & CEAT)

In service since 1983, the Dassault Aviation Mirage 2000 is derived in several versions and can carry out a wide panel of missions from air superiority interceptions to strategic ground strikes. Waiting for a large deployment of the Rafale, it is the essential vector for operational missions used by the French Air Force.
The initial qualification in fatigue was based on a full-scale fatigue test performed from 1981 to 1984 in the Toulouse Aeronautical Test Centre (CEAT). The fatigue spectrum applied had been built over the foreseen usage of the fleet, summed up in the technical specification written in 1976. The aim was to demonstrate 5,000 flight hours under this spectrum. Concurrently, all the fleet is under fatigue monitoring either with g counters or the more sophisticated Microspees system (cf § 6.6), as far as the Mirage 2000D is concerned.
The analysis of the damaging speed compared with the usage scheduled by the French Air Force pointed out the need to extend the life of this aircraft.
Several actions are being conducted with various schedules.
For one part, the load calculations have been re-evaluated with new and more accurate aerodynamic numerical codes developed for the Rafale. The results are being supported by in-flight tests.

For an other part, a new and more extensive inspection program is going to be developed to extend the life of the aircraft considering damage tolerance analysis.
Last but not least, a new fatigue test is going to be conducted to identify new potential critical points in fatigue, to support the damage tolerance analysis and to validate repair solutions. The test will be performed on an aircraft retired from service. One of the main difficulties consists in taking into account the various usages and versions of the aircraft with a single full scale test. The test rig installation is in progress (figure 42), starting actual fatigue test is scheduled in November 2005.
Life extension of the landing gear (taking into account the quite important increasing of the weight of this aircraft) is carried out with specific fatigue tests. These tests are run to substantiate the increase of the number of landings from 4,200 (already proved for the initially specified load level) to 9,000. Dassault Aviation used all flight measurements available in order to update the stress levels to be applied during testing. These data are part of the experiments run on the ground : rolling, braking, overloading during take off, touchdown, pivot, etc. The first cycles have been applied on the nose landing gear in February 2003. The main objective reached in June 2004 was to simulate three aircraft lives to release potential for the fleet. In April 2005, 45,000 landings necessary to substantiate the increase of landings up to 9,000 (representing five aircraft lives) have been simulated.

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

The new Dassault Aviation three engine powered business jet named Falcon 7X is designed to fly 5,700 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 will be carried out on a single full-scale test article as it has already been done for the Falcon 2000. Under a Dassault Aviation contract, CEAT has carried out the test rig engineering composed of 64 hydraulic jacks + fuselage pressurisation (figure 43) and around 2000 measurements (strain gauges and displacement sensors). The fuselage and wings of the airframe were received at CEAT end of November 2004. The assembling of the test rig started in June 2004 and preliminary static tests to clear the beginning of the flight test programme started only two months and a half after airframe assembling by Dassault staff. A first sequence of 40,000 flights representing two aircraft lives and that should last about one year is currently in progress. This fatigue phase will be followed by the static strength demonstration up to Limit and Ultimate Loads, then, a damage tolerance phase will follow to cover 20,000 flights more.

6.5.6 European project Tango (CEAT)

TANGO (Technology Application to the Near Term Business Goals and Objectives of the Aerospace Industry) is a RTD program (Research, Technological development and Demonstration). This research project half funded by the European Community aims at promoting competitiveness, sustainable growth and new perspectives on aeronautics through the improvement of the structural efficiency through reducing by 20% manufacturing costs and weights. It is divided into four parts corresponding to airframe parts likely to induce weight reductions and costs such as composite lateral wing box including a metal to composite joint, a composite centre wing box, a composite fuselage section and a metallic fuselage optimised in glare material. In this project, the contribution of CEAT consists in the structural assessment of the composite central wing box by performing static and fatigue damage tolerance tests up to 300,000 cycles divided into fifteen sequences based on positive gust loading case. The 16 meter long TANGO demonstrator weighing more than 36 tons has been equipped with 2000 channels (strain gauges) and about 50 displacement transducers. The local loads specified for the tests being higher than the capability of the strong floor, a self supporting test rig has been designed. This demonstrator is positioned on the rig by six instrumented reaction fixtures which make it possible to check in real time the quality of the loading during tests. The whole test installation can be seen figure 44.
This project, involving thirty aeronautical companies belonging to twelve different Nations, started in May 2000 and the last fatigue test cycling which started in September 2004 is planned to be completed in 2005.

6.5.7 Certification tests of the A380 engine pylon (Airbus and CEAT)

The first certified aircraft version A380-800 is fitted with new Rolls Royce Trent 900 engines. One specimen which is an inner pylon box with the wing mounts and the thrust fittings will be tested to simulate the structural behaviour in fatigue and damage tolerance. The pylon will be tested during 57,000 flights corresponding to three aircraft lives. During the damage tolerance phase, around fifteen artificial damages will be introduced on the structure at the beginning of the fatigue test to know the behaviour of cracks in specific zones, and perhaps extended if no propagation happens. CEAT is being designing the test rig installation (figure 45) to load the specimen on the engine mount interfaces (fwd and rear engine mount, spigot) through 6 hydraulic jacks and ensure a precision of more or less 1% on the loads. The specimen will be equipped with about 300 measurement channels including gauge bridges, strain gauges and displacement transducers. The first life will have to be simulated before delivery of the A380 certification, planned in 2006. The other two lives to be simulated will last until 2007.

6.6 IN-SERVICE AIRCRAFT FATIGUE MONITORING

6.6.1 System general description and data collection (CEAT)

Three systems are currently used in the French Air Force : original g counters for most of the fleet, a multichannel systems (5 analogic channels + 7 binary parameters data, no strain-gauge), named MICROSPEES for the Mirage 2000D fleet, and a much more sophisticated system named Harpagon for the Rafale.

The main improvements for Harpagon are the following :

- more parameters recorded (around 30),
- more structural points tracked (around 20),
- day-to-day assessment of the fatigue remaining potential and inspection interval performed by the Air Force and Navy themselves. These values are periodically updated by feed back and comparison to more extensive calculations performed by CEAT.

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

6.6.2 Evaluation of the arbitrary mass proposed for the full scale life extension test of the Mirage 2000 fleet (CEAT)

For the life extension test of the Mirage 2000 aircraft, the fatigue spectrum applied to the airframe is based on an arbitrary constant mass level, defined by Dassault Aviation depending on the stores configuration used for each flight.

Thanks to its advanced fleet fatigue monitoring system used for the Mirage 2000 D, named Microspees, the CEAT proposed to assess the degree of conservatism of this mass level. Effectively, Microspees works with a time dependent data recording that allows to use a mass profile evolution for each flight and each tracking point. This item offers a better accuracy in the calculation of load distributions and thus on the evaluation of fatigue damages.

With minor modifications to the calculation software, both approaches for the calculated mass were available : arbitrary constant mass and time dependent one. The test sample was composed of one year of flights realised in three squadrons and the basis of comparison was the Fatigue Indices obtained on the different aircraft with both mass hypothesis.

Arbitrary constant fuel mass and real recorded values versus flight time are shown figure 46.

The results validated the manufacturer’s hypothesis and allowed to quantify the severity level of the fatigue spectrum to be applied for the life extension test.

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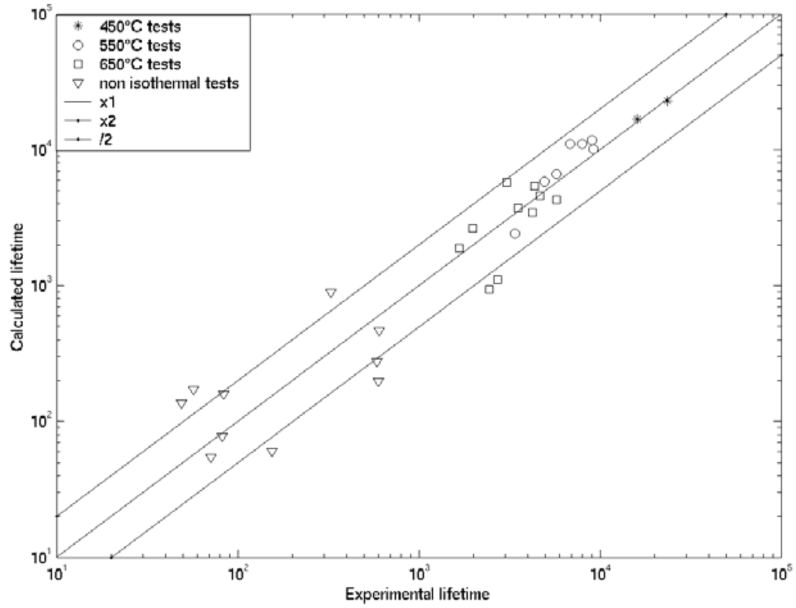


Figure 1 : Extension of a crack growth model with fatigue-creep-environment interaction to non isothermal loading
Comparison between calculated and experimental lifetimes

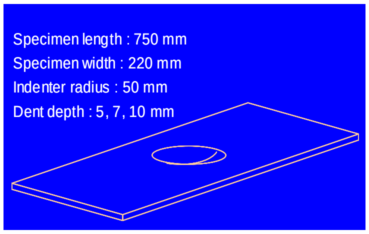


Figure 2 : Specimens for dent effects assessment

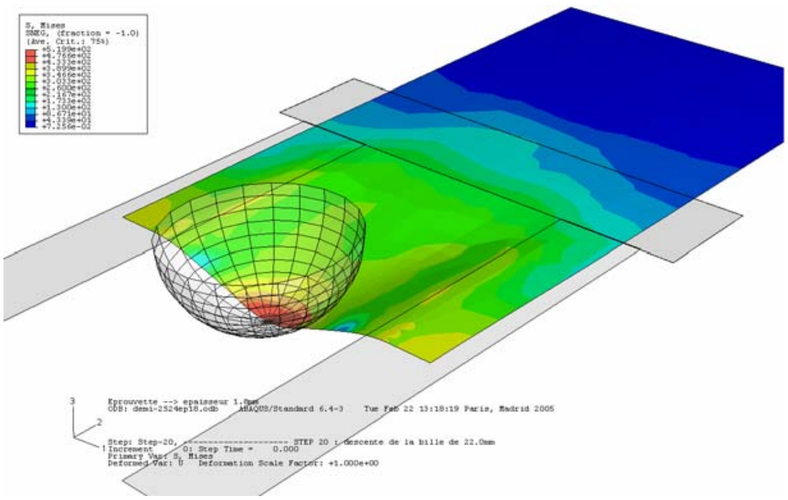


Figure 3 : Dent effects assessment : comparison of calculated and experimentally applied forces plus achieved dent depth.

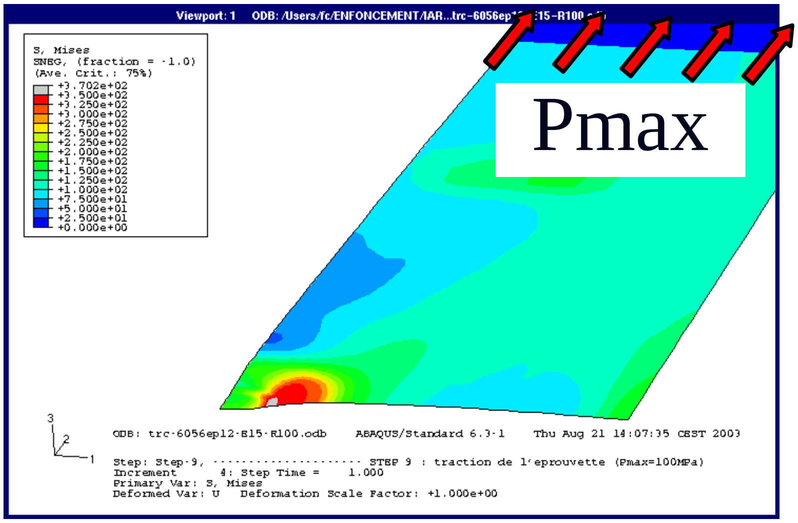


Figure 4 : Dent effects assessment : comparison of calculated and experimentally applied forces plus achieved dent depth (cont'd)

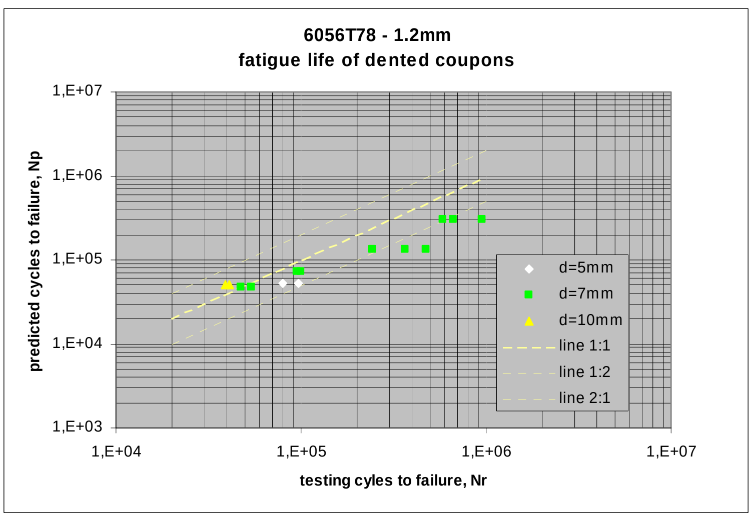


Figure 5 : Effects of dents, fatigue test results

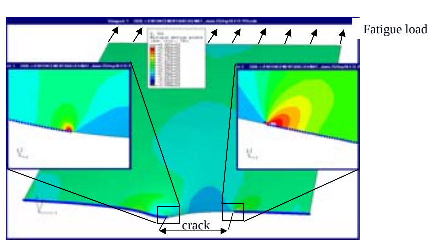


Figure 6 : Dent depth effects : Calculation of the stress intensity factor at each crack tip at three locations within the thickness of the skin

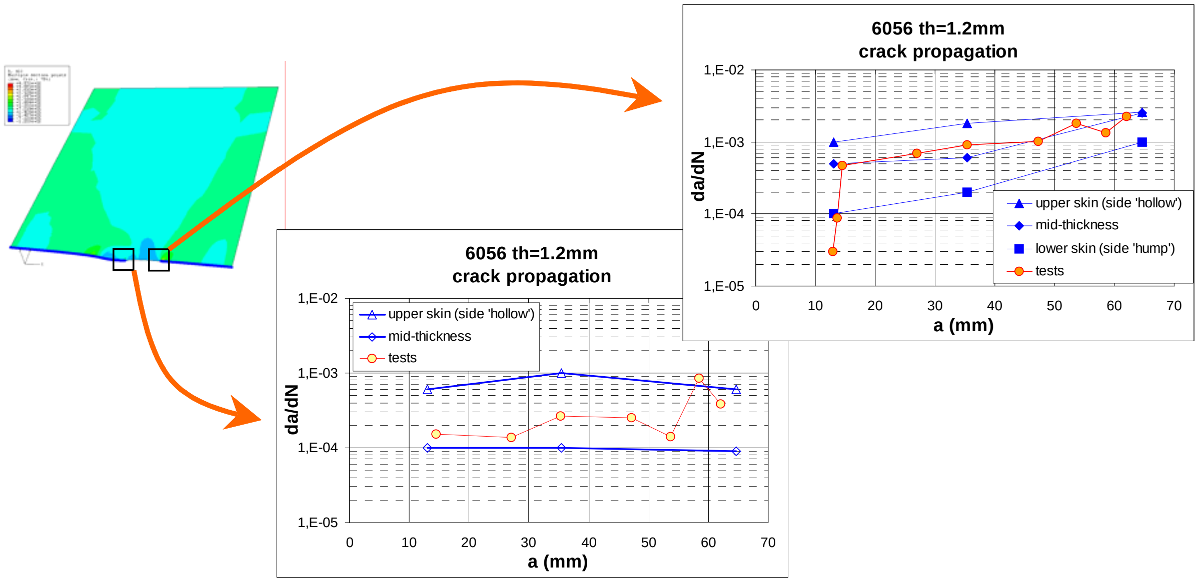
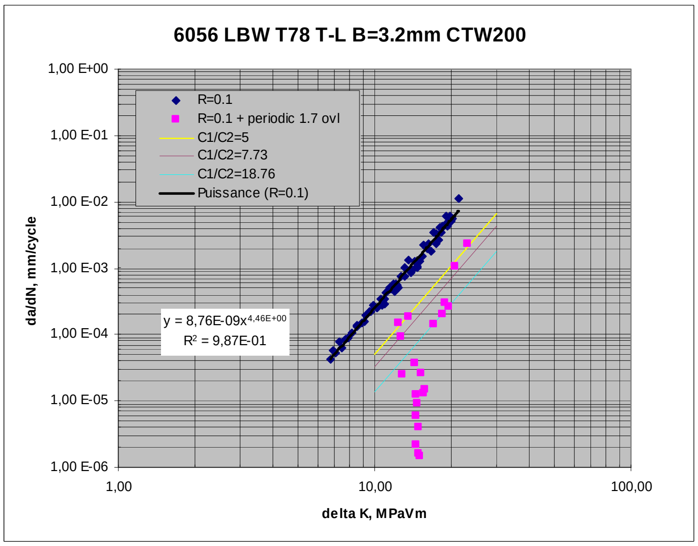


Figure 7 : Dent effects assessment : comparison between prediction and experimental data



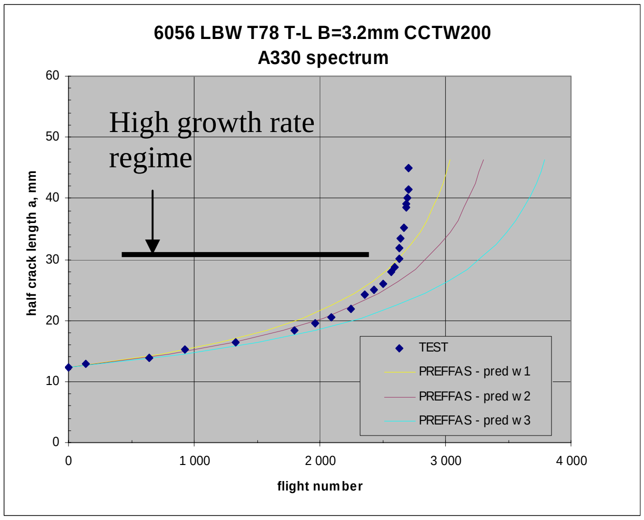


Figure 8 : Spectrum loading

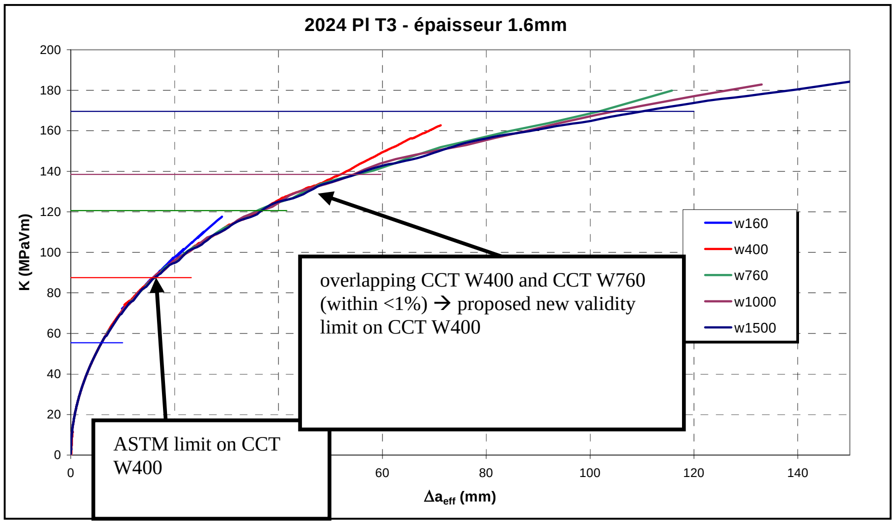


Figure 9 : R curve extrapolation

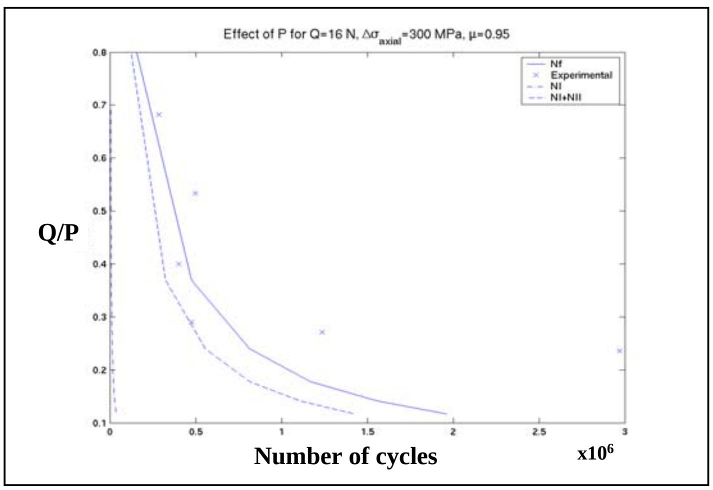


Figure 10 : Fatigue fretting

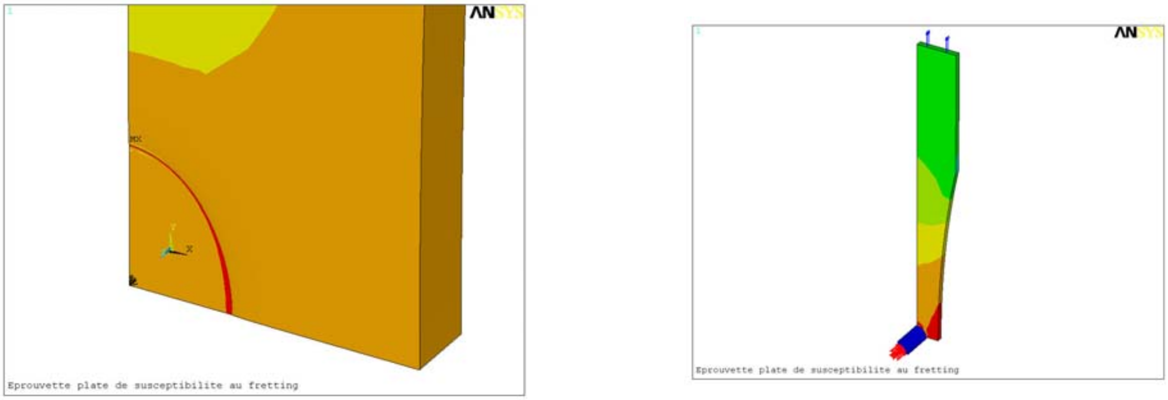


Figure 11 : Numerical modelling of the friction pads tests

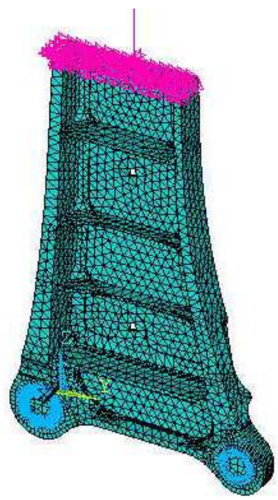


Figure 12 : Numerical modelling of the wing spar

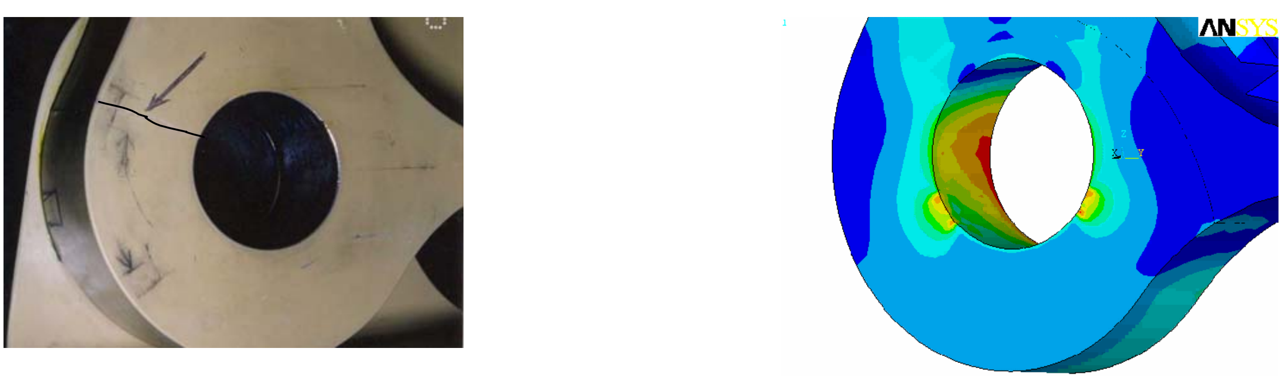


Figure 13 : Correlation between calculation and initiation site of the wing spar

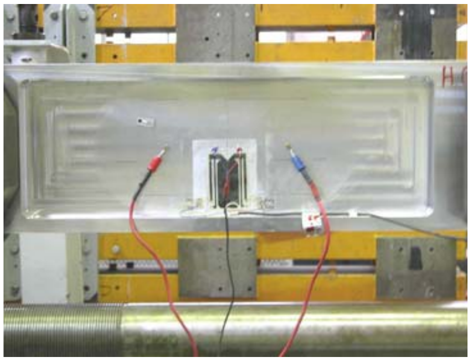


Figure 14: Bialveole specimen

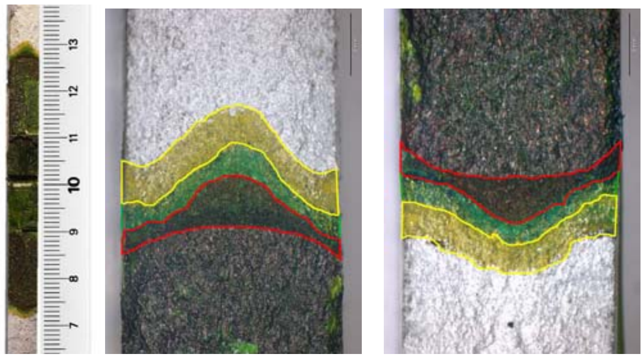


Figure 15: Image analysis for stable tearing

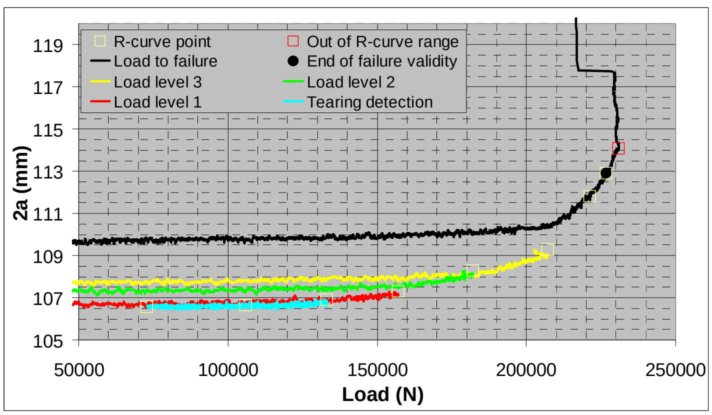


Figure 16: Tearing = f(load)

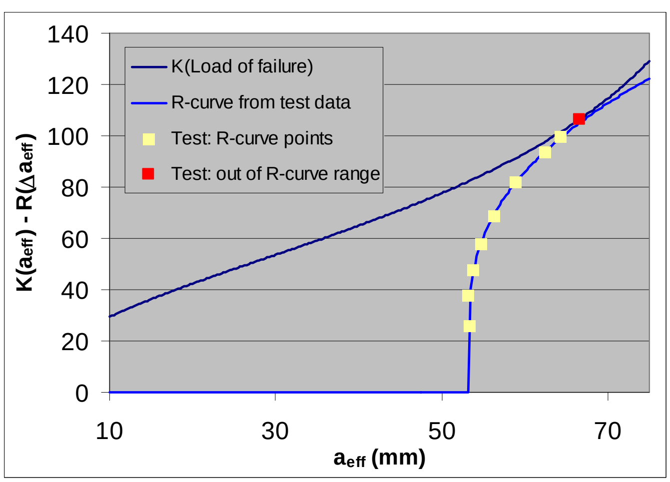


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Figure 17: R = K(a_{eff}) , R curve data processing

Figure 18 : Test installation for a four-point bending position of the aluminium specimen

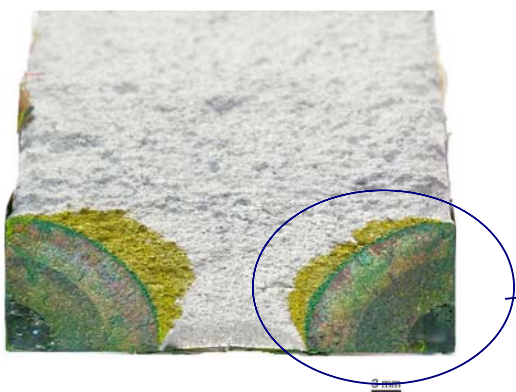

Figure 19 : Specimen section failure by fatigue growth and static tearing of the two corner cracks.

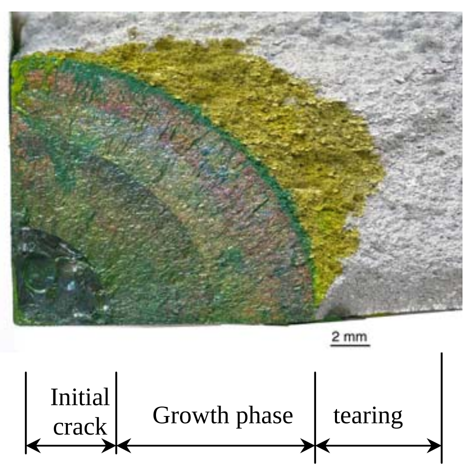

Figure 20 : Growth and static tearing coloration.

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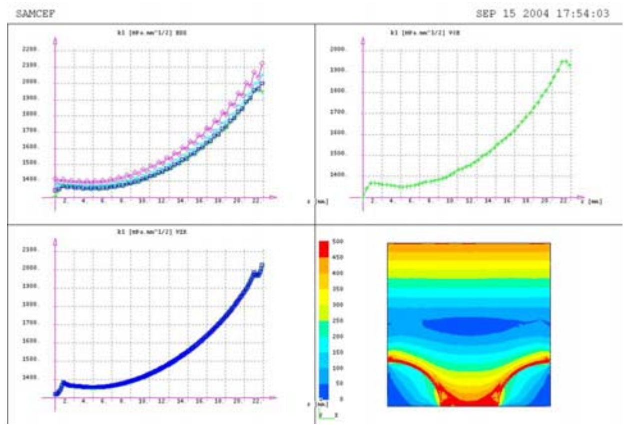

Figure 21 : Strength Intensity Factor computation with SAMCEF

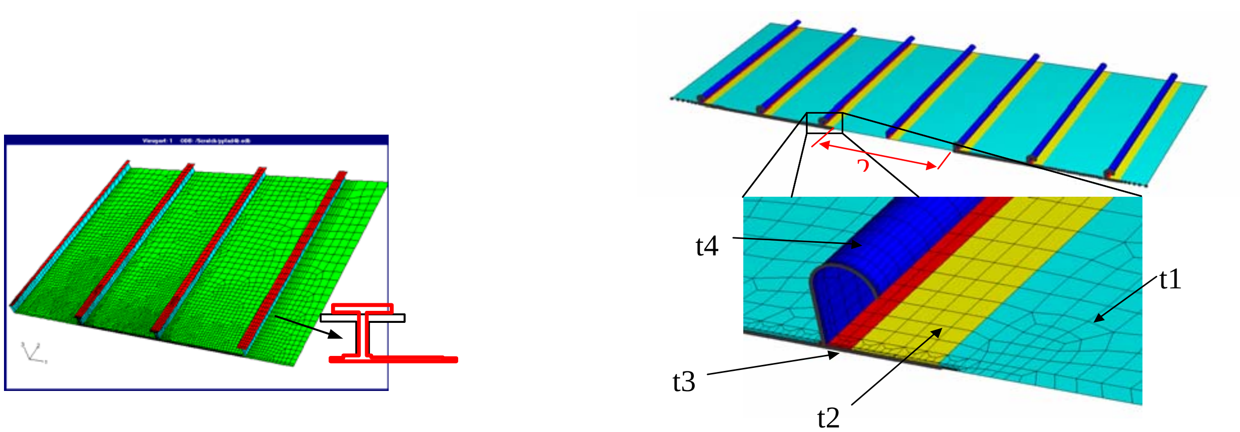

Figure 22 : Residual strength of welded stiffened panels

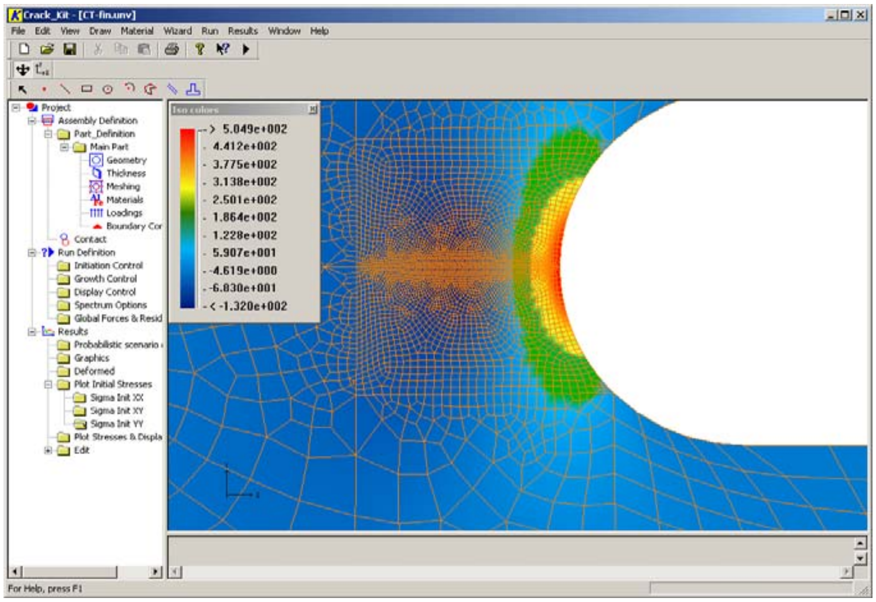

Figure 23 : Development of EADS CCR in-house BEM, a screen shot of CRACK-KIT

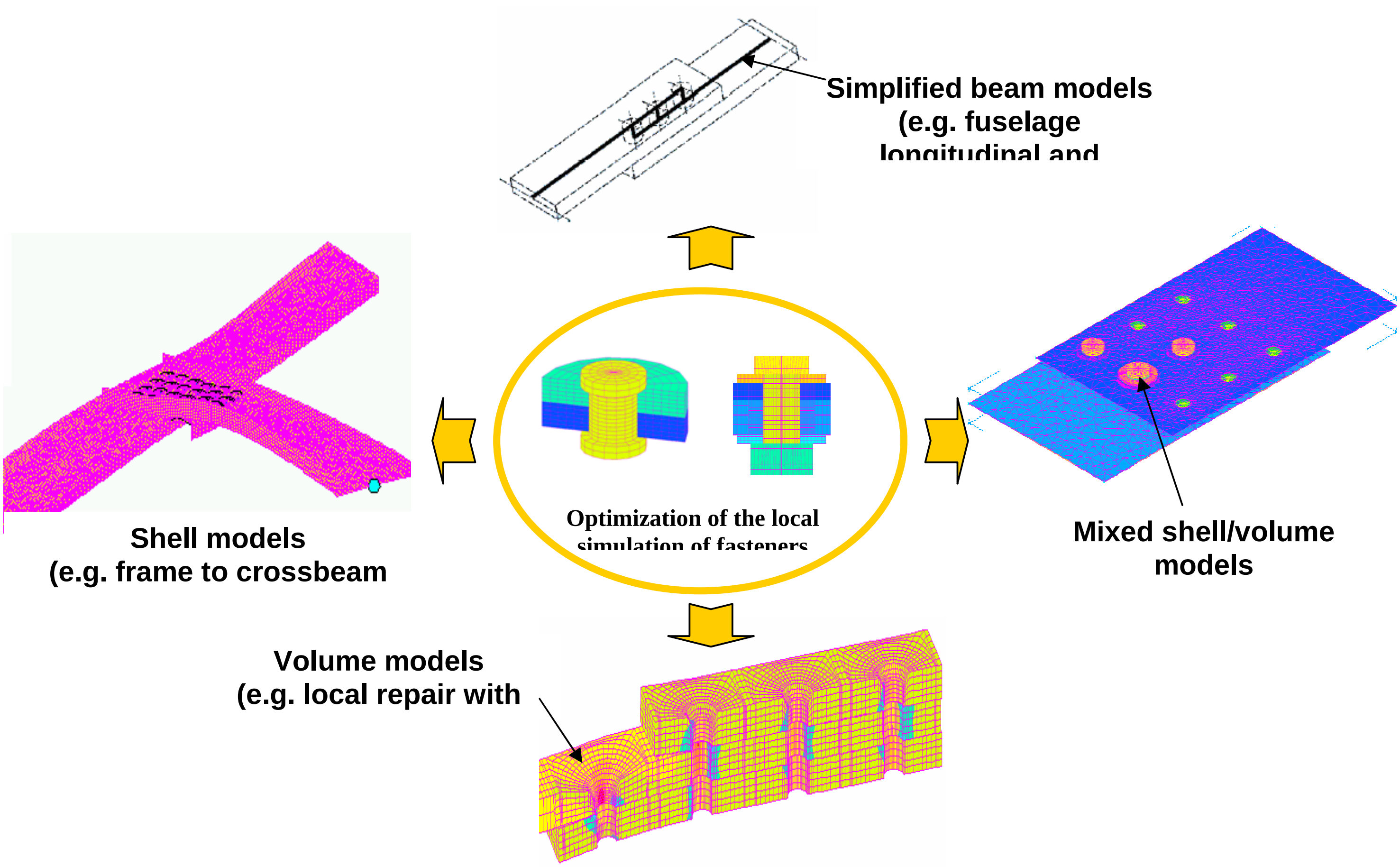

Figure 24 : Numerical tools for improvement of fatigue assessment of riveted and bolted metallic joints

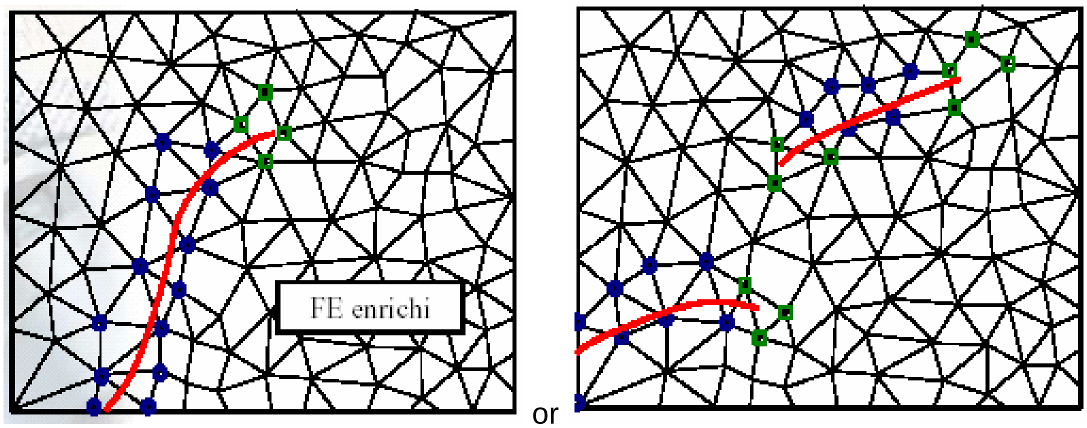

Figure 25 : Nodes enrichment along the crack path

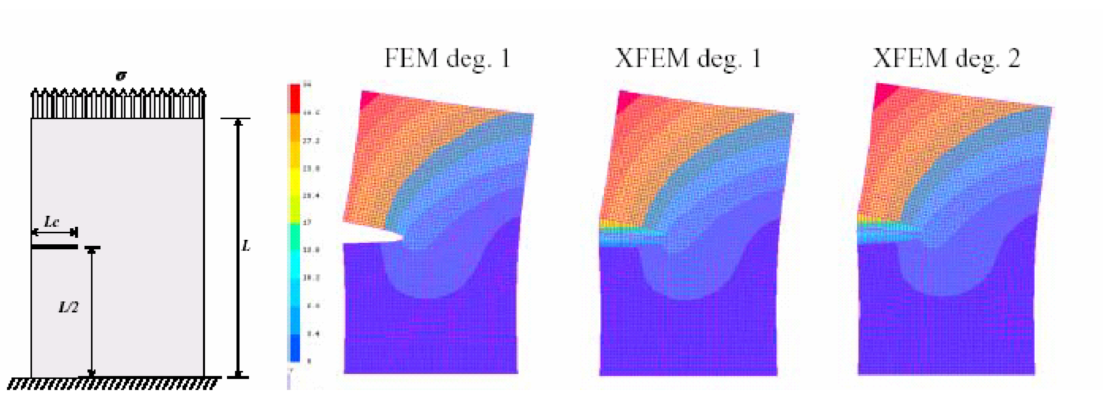

Figure 26 : Single edge notch specimens, comparison of displacement fields between FEM and XFEM

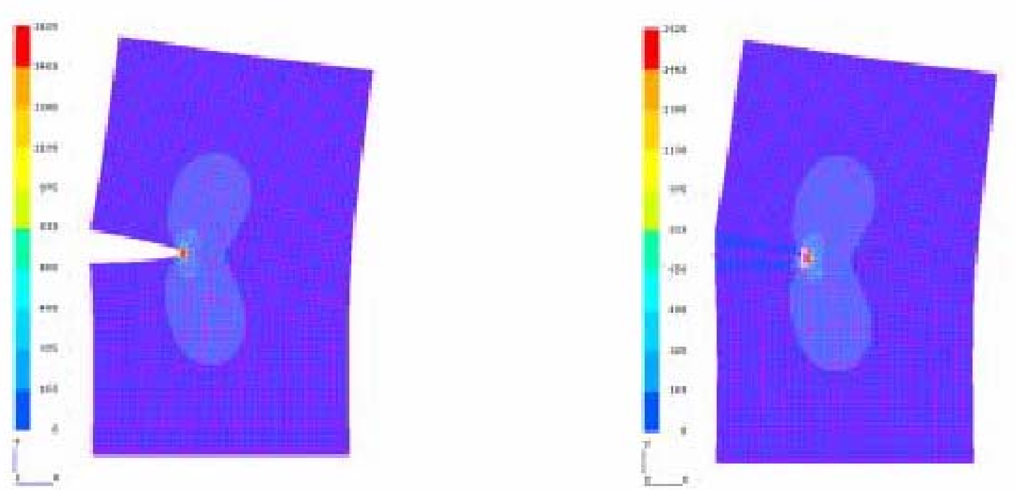

Figure 27 : Single edge notch specimens, comparison of Von Mises Stress between FEM and XFEM

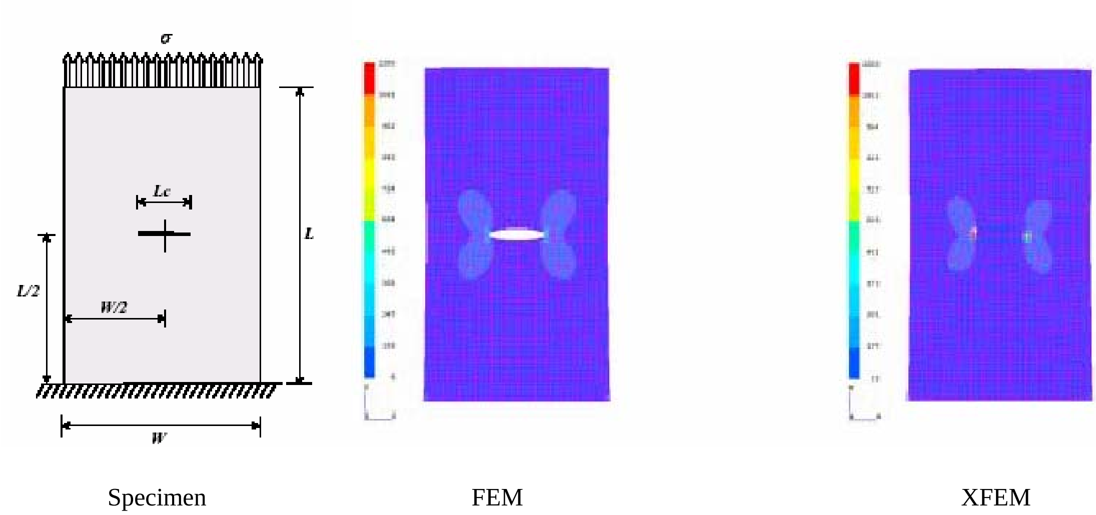

Figure 28 : Center Crack Growth Specimens, comparison of Von Mises Stress between FEM and XFEM

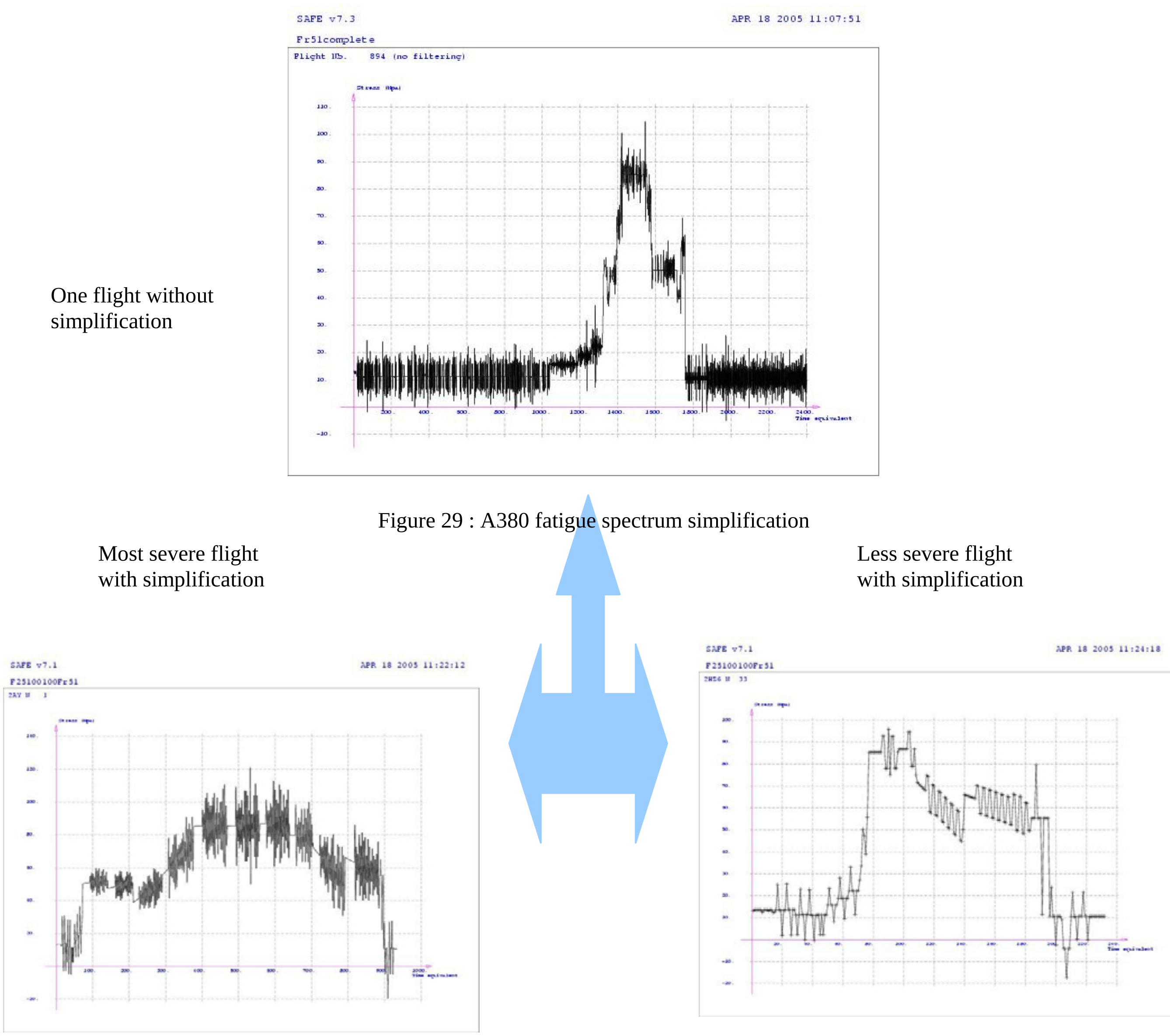

Figure 29 : A380 fatigue spectrum simplification

Figure 31 : Test samples

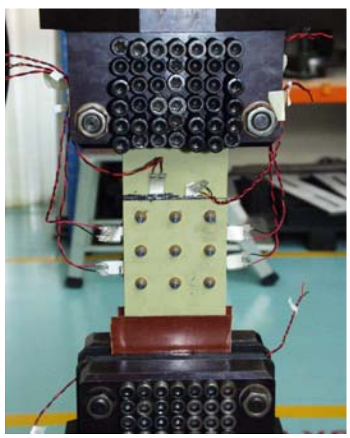

Figure 32 : Test in progress

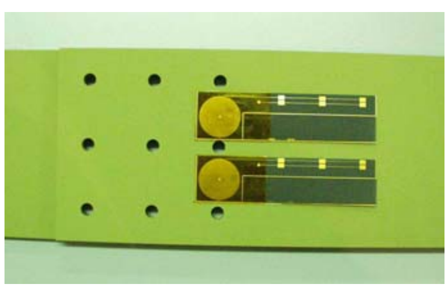

Figure 33 : Foil eddy current sensors

Figure 34 : Alphajet Full Scale fatigue test

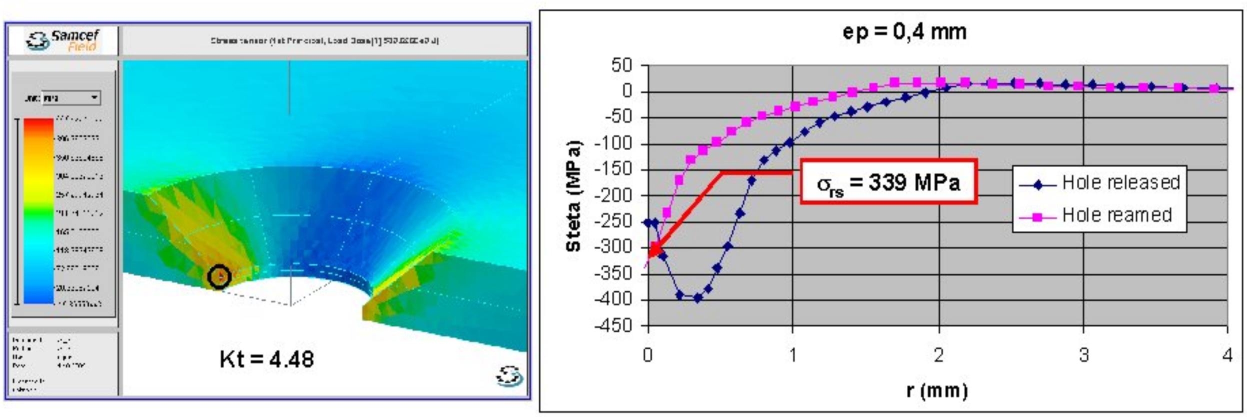

Figure 35 : Alphajet, tangentiel residual field near the hole

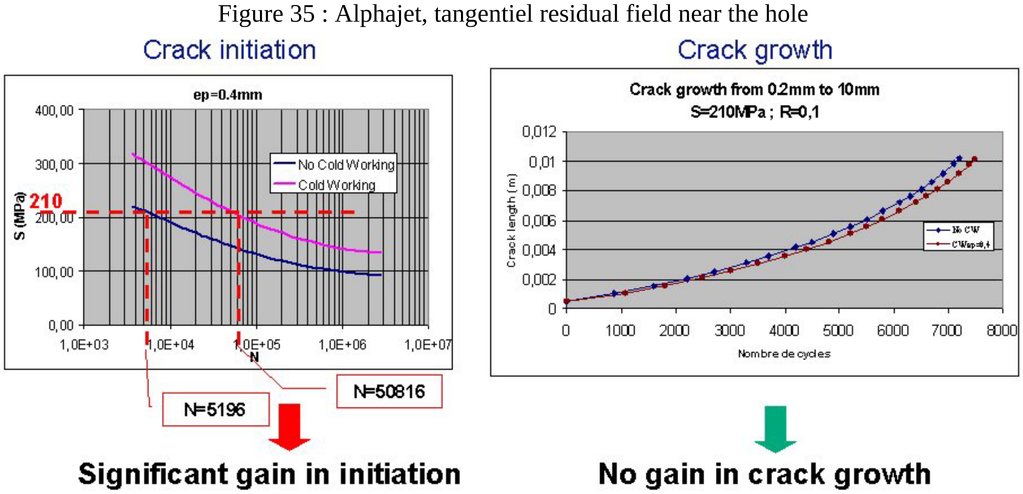

Figure 36 : Alphajet , cold working benefit

Figure 37 : The Transall full-scale test

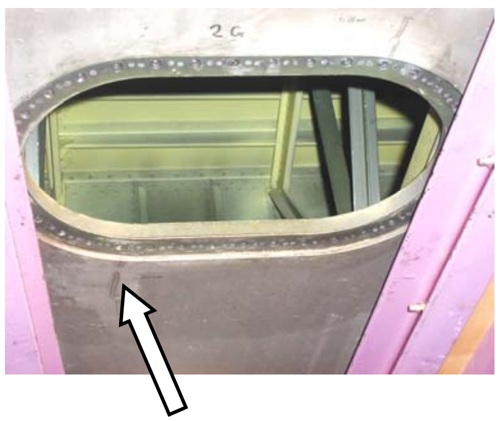

Figure 38 : New fatigue damage at 34,000 simulated flights

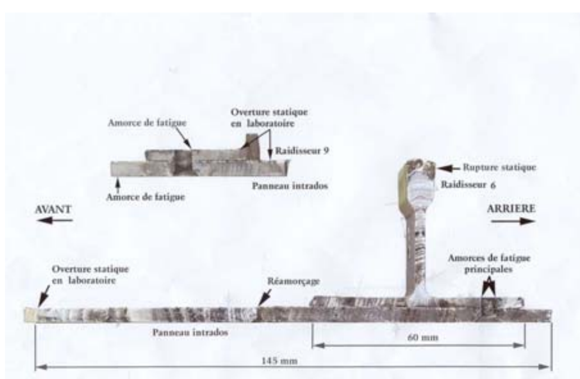

Figure 39 : Fractographic investigation

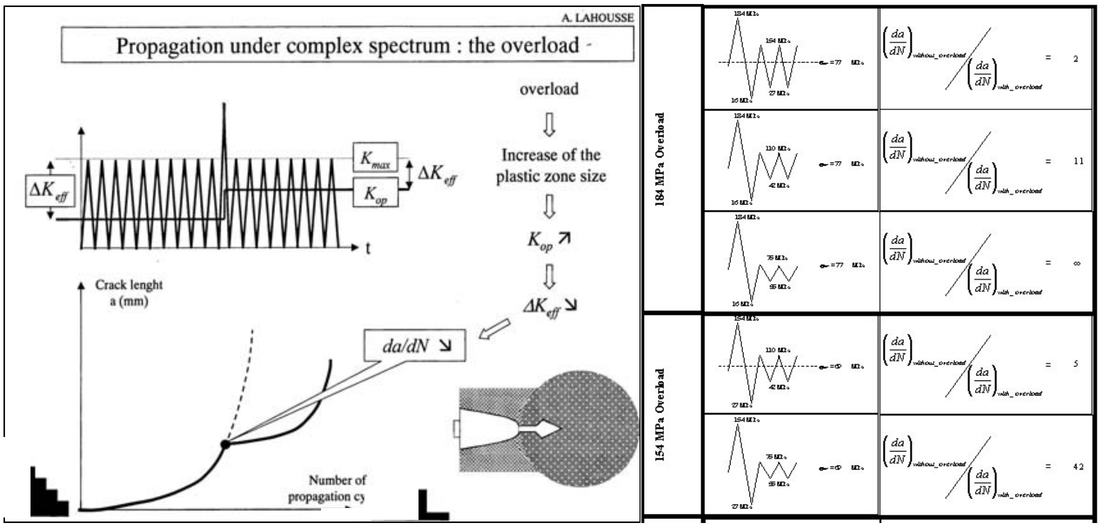

Figure 40 : Overload effects

	Door Reinforcement	Stringer N° 6
Number of flights	Distance to initiation (mm)	
0	0,55	0,01
2000	0,6	0,03
4000	0,66	0,06
6000	0,73	0,10
8000	0,79	0,14
10000	0,88	0,19
12000	0,99	0,29
14000	1,18	0,41
16000	1,38	0,75
18000	1,76	1,06
20000	2,23	1,37
22000	2,81	1,80
24000	4,00	2,29
26000	6,80	3,00
28000	8,40	5,50
30000	10,00	14,00
32000	12,00	22,00
34000		

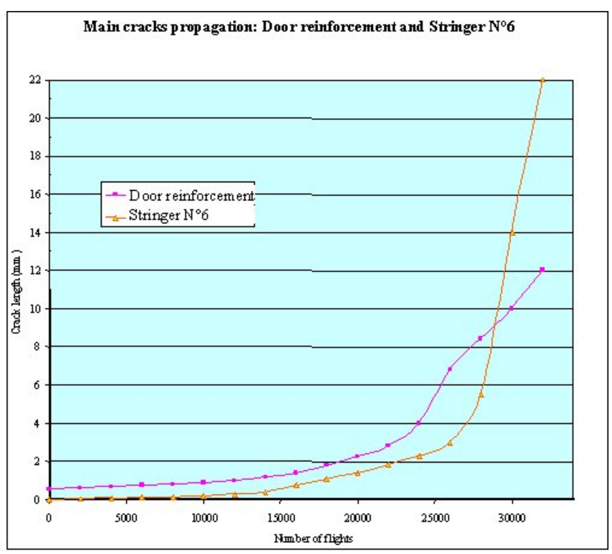

Figure 41 : Growth history of the crack in the area under concern

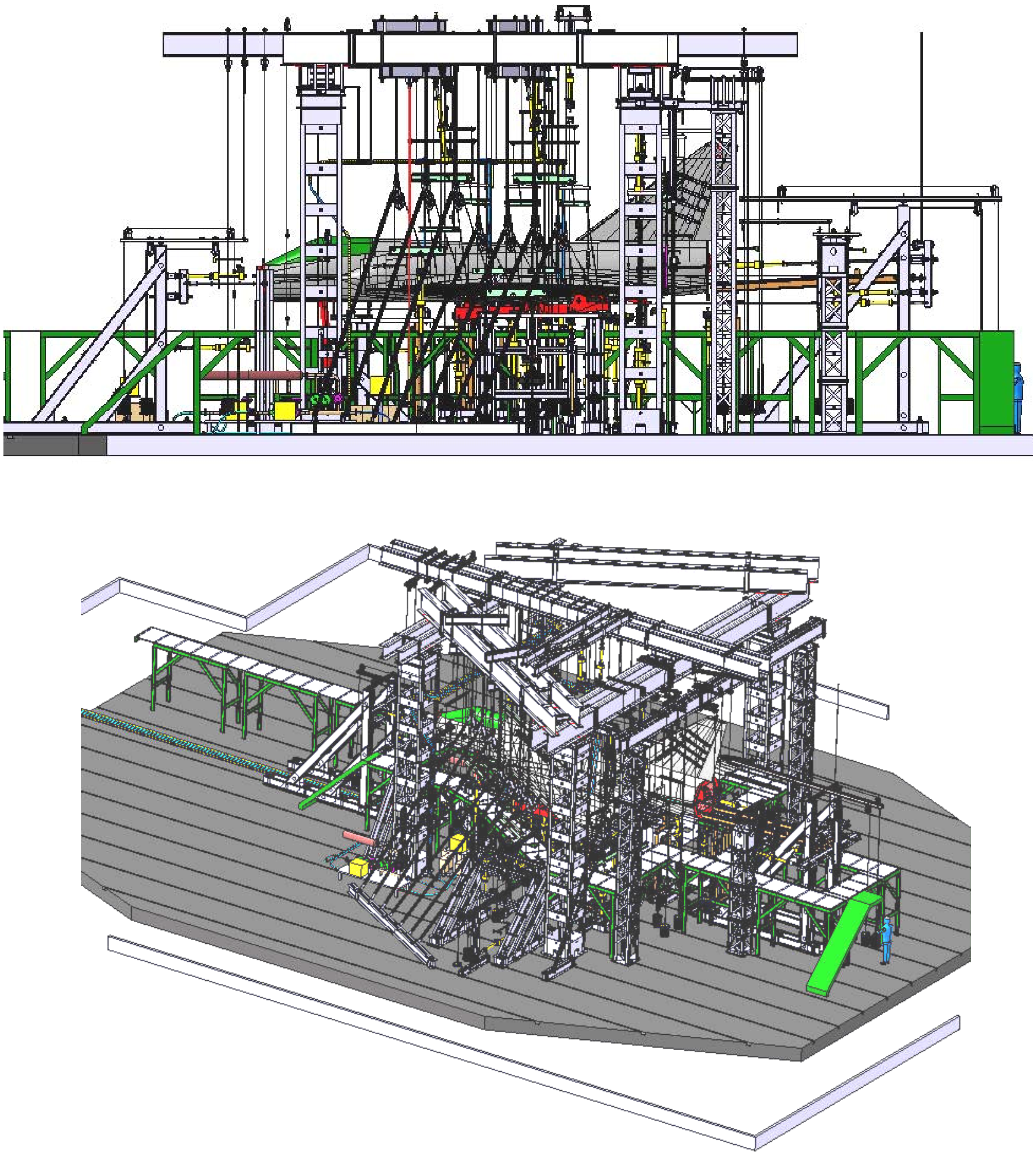

Figure 42 : Mirage 2000 fatigue test rig

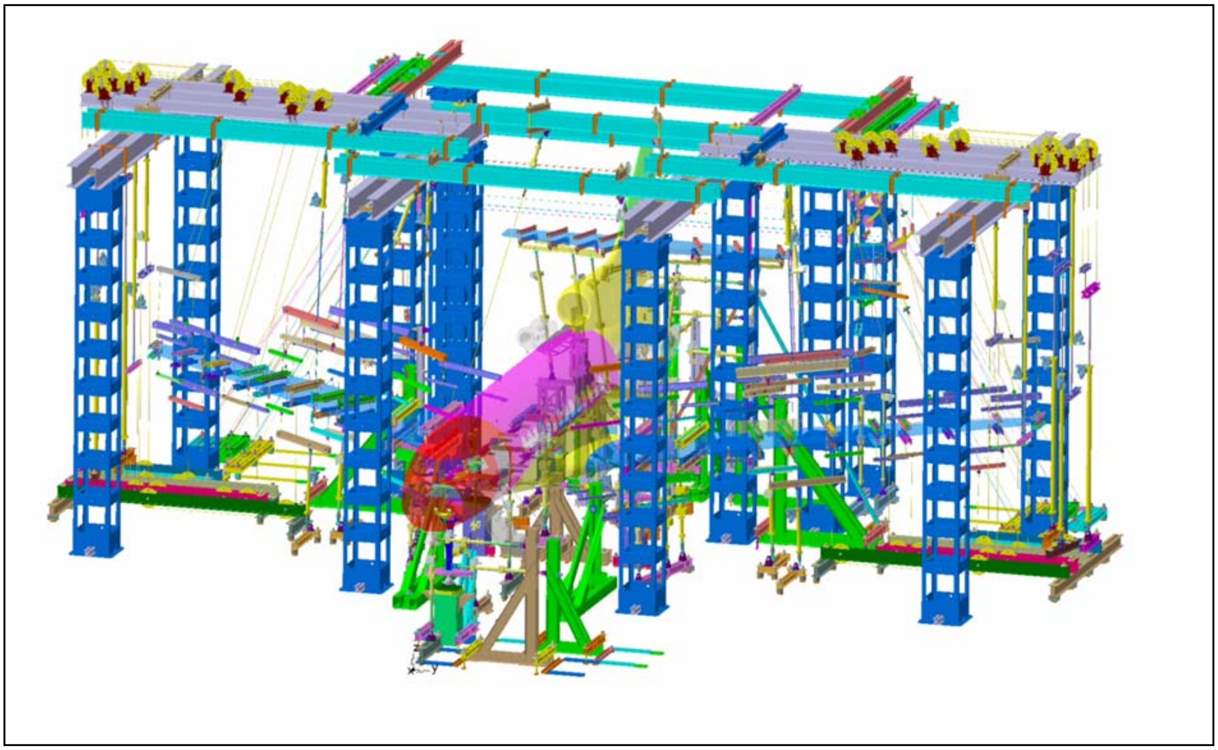

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Figure 43 : F7X static, fatigue and damage tolerance test

Figure 44 : tango programme static and fatigue/damage tolerance test

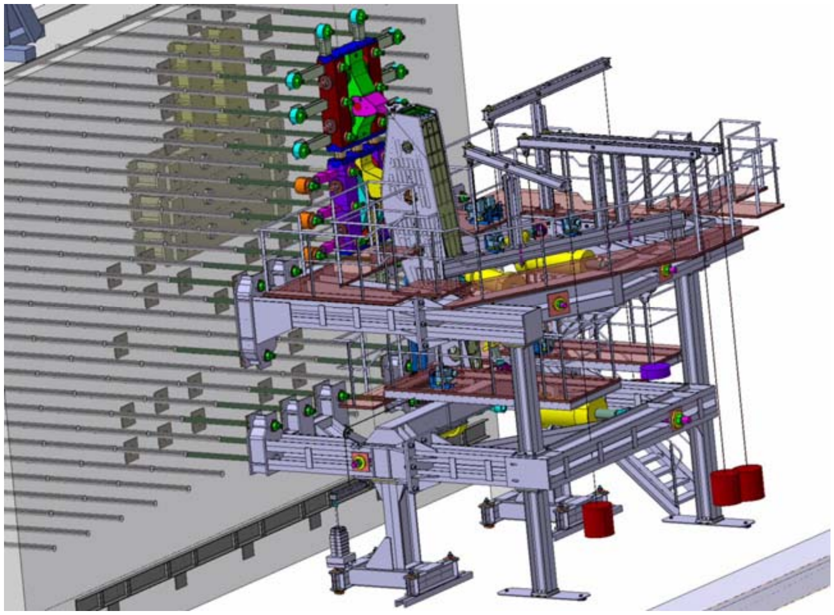

Figure 44 : Fatigue and damage tolerance test on A380 pylon

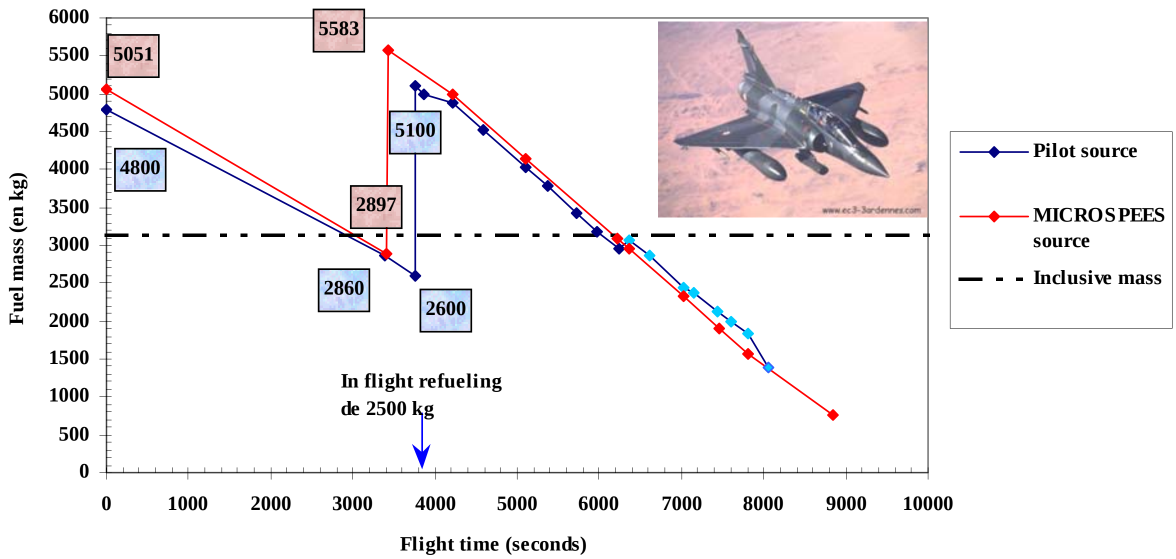

Figure 45 : Mirage 2000, assessment of store weight effect assumption