

DEVELOPMENT OF A ROBUST MULTIAXIAL FATIGUE MODEL FOR A/C METALLIC ASSEMBLIES IN AN INDUSTRIAL CONTEXT

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Abstract

In a context of growing importance of mass reduction and reliability of structures towards greener aircrafts, fatigue of metallic materials is a key issue in the structural optimization. The process used by aeronautic industrials to compute the fatigue life is often based on a large empirical experience and meets a need for efficiency in their application, requiring a compromise between accuracy and ease of use.

According to legacy crack initiation methodologies, lifetime computation is based on the analysis of elastic stress fields, calculated analytically or by Finite Element Method. Evaluation of lifetime is calibrated on elementary tests, mainly uniaxial, with geometric specificity (bone, hole, notch...). One of the limits of this approach appears when parts are subjected to multi-axial loads. Nowadays, these particular stress states are justified by conservative approaches to ensure flight safety and by tests on full-scale aircrafts.

Whether for the operational maintenance or the structural optimization of new aircrafts, it is intended to enhance crack initiation methodologies, taking into account multiaxiality of loads, stress gradient effects, and complex material behaviours. Dassault-Aviation implements a crack initiation lifetime computation based on a local approach. These developments go hand in hand with a PhD (Nutte, 2023) on a multiaxial fatigue criterion in order to predict crack initiation in metallic assemblies.

This work was supported by an innovative dedicated test campaign. The identification of material's parameters is based on uniaxial and multi-axial mechanical tests, specifically designed to calibrate these models. Then, novel geometry of specimen for bolted assemblies, facilitating various biaxial non-proportional loadings, is used to evaluate the methodology.

Also, multiaxial fatigue models require a precise assessment of the local mechanical fields to which the structure is subjected. For this, a finite element analysis must be conducted with a level of complexity associated with the level of accuracy targeted. The material constitutive equations used in the finite element analysis are therefore at the heart of these fatigue substantiation approaches.

Applications to complex aeronautical structures such as massive 3D parts or assembly by fastener will highlight the benefits and perspectives for this local fatigue approach. It will require the use of multi-scale data science.

Keywords: Fatigue, Local, Junction, Multiaxial, Test.

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FATIGUE LIFE EVALUATION IN INDUSTRIAL CONTEXT

Fatigue in an industrial context

In Dassault Aviation civil or military aircraft, the number of fasteners surpasses 200 000. This underscores the critical importance of sizing and substantiation for the structural design office. Joints serve two primary functions: building the aircraft's structure by positioning parts together and transferring loads between these parts. Loads on joints are determined through analysis of aerodynamic forces.

For Dassault Aviation's stress department, the challenge is to predict the initiation of cracks under repeated fatigue loads. The methodology should demonstrate that the aircraft is able to withstand these loads throughout its entire lifespan. In an industrial context, crack initiation refers to the appearance of a macroscopic crack in the parts. The studies involve predicting a lifetime, expressed in cycles, flights, or life, associated with the fatigue spectrum under a defined level of load.

Fatigue crack initiation is commonly represented using the SN curve (also known as the Wöhler curve). To determine the fatigue behavior of metallic materials, fatigue load spectra at several levels are applied to elementary specimens. A materials database is built to understand the performance of each material used in metallic parts subjected to fatigue loads.

The basic way to predict fatigue lifetime of a part is to compute the maximum stress inside and to compare to the number of cycle determined by test, directly on a corresponding SN curve. However, for mechanic parts, crack initiation appears either on a geometrical singularity or on a material default (corrosion for example). Geometrical singularity could be a hole, a notch, a change in thickness, hole filled by a fastener...etc., which induces over stress and gradient close to it. Methodologies used in crack initiation have to take into account these various stress fields because they are a critical factor in determining the fatigue lifetime of a part. Furthermore, it is clearly impossible to test all fatigue load spectra on all materials of an aircraft, as this would lead to an infinite number of combinations. Therefore, methodologies must also take into account spectrum treatment.

Lap joints features

As explained previously, a crack can occur close to geometrical singularities. For a lap joint, the singularity is the hole with the fastener inside. The load on a lap joint is decomposed into two main contributors:

- By pass load,
- Transferred (or bearing) load.

The by-pass force is the one that remains in the plate and is transmitted to the subsequent row of bolts or results from equilibrium by strain compatibility of the assembly. It induces an overstress with gradient close to the hole. The bearing force constitutes the part of the load transmitted through contacts between bolt and plates. When bearing load is applied, either combined to by-pass load or not, secondary bending is generated to realign the neutral fiber of the assembly. These effects modify the stress field close to the hole and the combination leads to different crack initiation locations.

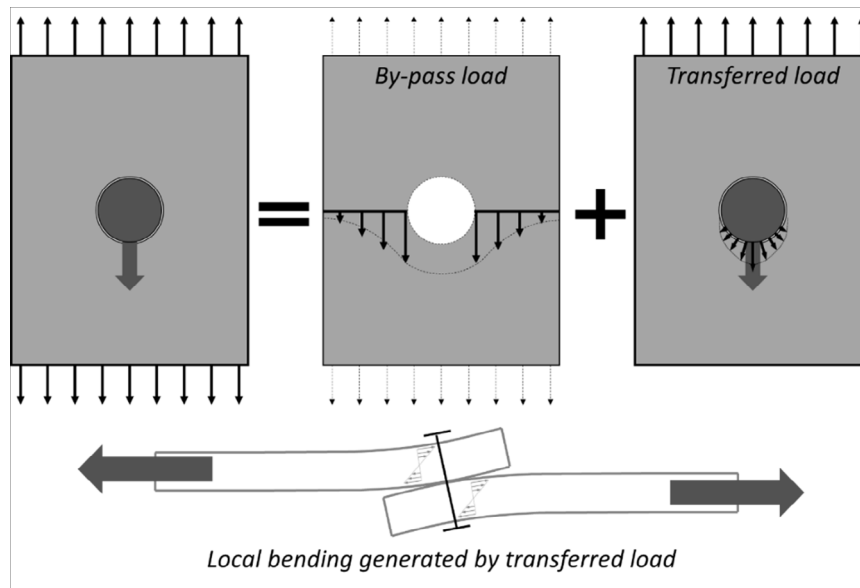


Figure 1. Basic equilibrium of a lap joint.

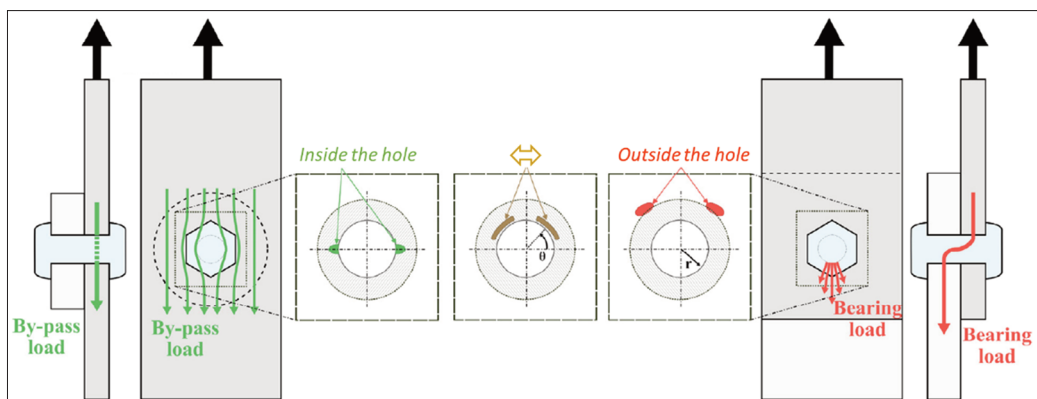


Figure 2. Crack position.

Two main crack initiation locations occur: inside the hole and outside the hole. Inside the hole location is caused by the by-pass load because over stress on both side to the hole leads to the crack initiation. Outside the hole, location is driven by the bending stress in the plate. The extreme configuration with outside the hole location is the unfolding of bolt angle. Finally, in aeronautical parts, the location of crack is between these two states, inside and outside the hole.

Actually, the parts of an aircraft may be in various equilibrium states. Figure 3 shows some examples of these typical equilibrium states: supported, unsupported, end to end joints, with or without transferred and/or by pass load... etc. All these states exist on aircraft, some architectural nodes are a combination of them and lead to a complex equilibrium and stress fields. We can cite the link between a strong frame and a stringer in the fuselage or a strong rib and a wing spar as examples. The variability of these equilibrium states is combined with the variability of load during a flight. The same parts can be subjected to different mechanical stresses, such as traction, shear, and unfolding, within the same fatigue spectrum. Loads can also be in phase or out phase.

This implies that crack initiation must take into account the combination of basic equilibrium states to be accurate on aircraft assemblies.

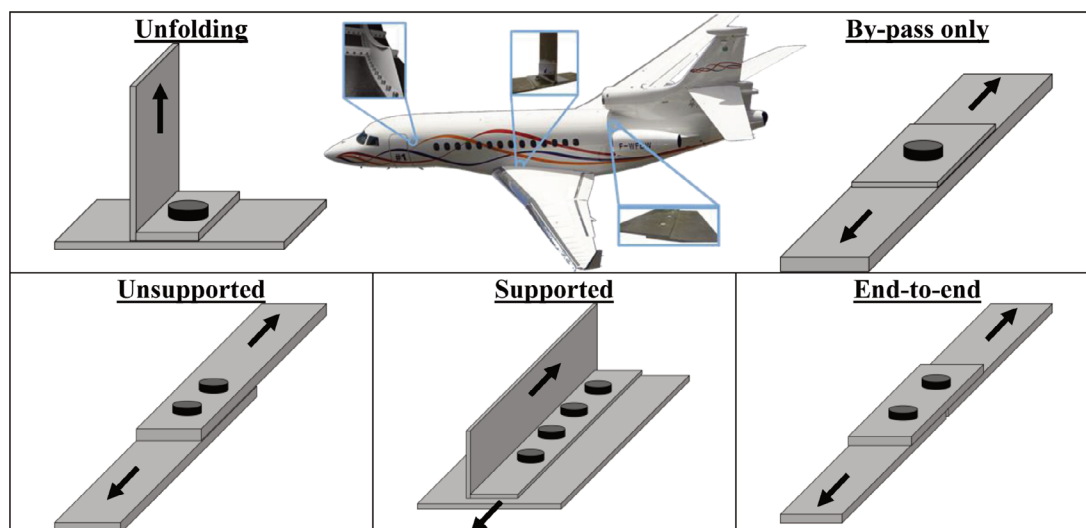


Figure 3. Aircraft lap joint.

In addition, location and lifetime are disturbed by all technological parameters linked to a bolt assembly. The first of all is obviously the preload of the bolt, which generates benefic compression stress close to the hole. Combined with bearing load, the outside hole location is also favored, even if the bending is low. A fastener with a good preload force has better fatigue substantiation than a fastener with a low preload force. In addition, for screws, a large variation in preload force is often caused by the fitting process in the assembly chain. For rivets, the preload force is often more repeatable due to the way they are fitted. The fastener fitting with interference or clearance in the hole is also a crucial parameter for crack initiation. High clearance is detrimental for the lifetime of the assembly. At the end, aluminum plates have anodic oxidation to secure the parts to corrosion. This surface treatment is harmful for crack initiation. Methodology must take into account these special features of aeronautical lap joints.

Lap joint characterization in fatigue

As presented in the previous section, assembly features are complex issues, depending on many parameters that the aeronautical design department must control. Therefore, the design is governed by strict rules based on strong experience, extensive test campaigns and engineering judgment. Additionally, crack initiation methodology must be established on test specimens that should be as representative as possible of aircraft parts, sized for crack initiation.

The material is the first element to characterize in crack initiation. Elementary tests are performed on coupons: plate or cylindrical, with or without geometrical singularities such as holes or notches. These tests allow the stress department to establish the necessary methodology to predict crack initiation in “free edge” configuration. In “free edge”, all geometrical singularities must be understood, which produce overstress and preferred locations for crack initiation.

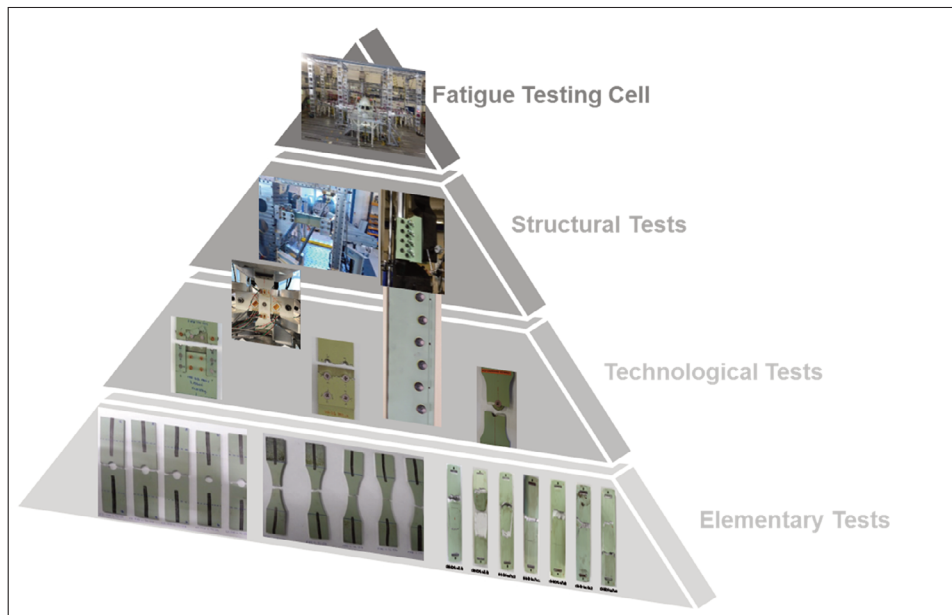


Figure 4. Test pyramid for lap joint in industrial context.

This methodology is not at the top of the agenda of this paper, but it is briefly presented in Figure 5. The stress engineer computes the stress field by Finite Element Method (FEM) or analytical means close to geometrical singularities on an aircraft part. This is an industrial methodology, used on many parts of the aircraft, therefore the stress field have to be easy to determine, which is why the input is an elastic stress state at the maximum fatigue load. Then, stresses are applied directly in the criteria. The methodology takes into account the spectral analysis, the material effect, and the gradient stress translation into plastic hypothesis. The output is directly the prediction of crack initiation. The methodology is set on elementary test database. The performance is good with the goal to have $0.5 \times N_{tests} \leq N_{comput} \leq 2 \times N_{tests}$.

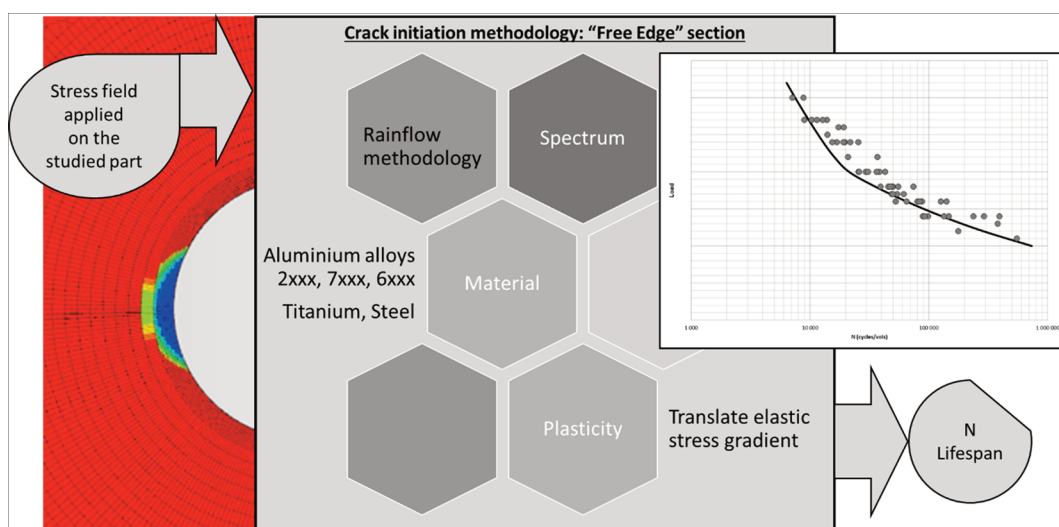


Figure 5. Crack initiation methodology for free edge and database performance.

As explained before, assembly is often treated as a particular case in crack initiation methodology. Test specimens are technological and represent the basic equilibrium detailed in Figure 3. Lap joint specimens must be fitted as they are done on aircraft, with exactly the same assembly range. To address all the equilibrium states and all parametric features, the test database must be substantial to obtain an accurate criterion of crack initiation in lap joint. Therefore, it is very expensive for aeronautical companies. Additionally, this means that all deviations from the test database must be addressed by new tests.

To validate the crack initiation methodology on critical aircraft assembly, structural tests are performed. They consist of a full-scale specimen of a particular area. For example, a portion of a wing box composed of a panel on a spar can be tested in bending to validate the lifespan computed with a methodology based on lap joint specimens. At the end of the proof of fatigue substantiation, a fatigue test cell is realized. It is a full-scale aircraft, loaded with a representative fatigue spectrum. This test is the final validation of the sizing of the aircraft.

Structural presizing methodology

At the beginning of an aircraft program development, sizing is mainly based on static attention. Fatigue study helps the stress department not to fail in presizing, which can be discovered later in the development. The methodology available at this stage must be easy-to-use for stress engineers and provide a secure conservative margin for the substantiation phase.

Presizing methodology is based on the computation of K_t , an overstress coefficient. Based on general loads, stress engineer computes local stress applied on the lap joint. The overstress coefficient helps then to determine an equivalent maximum stress close to the hole of the lap joint. This maximum stress is also compared to the associated [SN curve – spectrum] to obtain the lifetime of the parts.

The concept of this methodology is to combine the effect of bypass load and transferred load. As detailed in the previous section, they are the both components of basic equilibrium of a lap joint. Stress engineer shares the stress field into by pass and transferred stresses: α is the part of bearing load, $1-\alpha$ the one of by pass load. This proportion is now used in the computation of the overstress factor.

$$K_t = K_0 \left[(1-\alpha) \times K_{t-ByPass} + \alpha \times K_{t-Bearing} \right] \quad (1)$$

$K_{t-ByPass}$ represents the overstress caused by bypass load. It is based on chart 4.3 from (Pilkey, 1997).

$K_{t-Bearing}$ represents the overstress caused by transferred load. It is based on figure 9.12.12 and 9.12.13 from (Niu, 1998). Overstress caused by the bending of the fastener in the hole and the bearing in the joint plates is taken into account.

These K_t are based on literature and then tuned to capture particular effects due to aircraft lap joints.

K_0 is defined and set on test database to improve the accuracy for all different fasteners used.

The crack initiation is then computed by “free edge” methodology (Figure 5) with the stress field on the assembly defined by the stress applied and the K_t from equation (1). This methodology is simple and easy to apply because it is based on the hypothesis of a uniaxial load applied on a plate. The prediction of crack initiation is set conservative on the database, to prevent any risk in the pre-sizing phase of aircraft development. The performance is plotted on Figure 6.

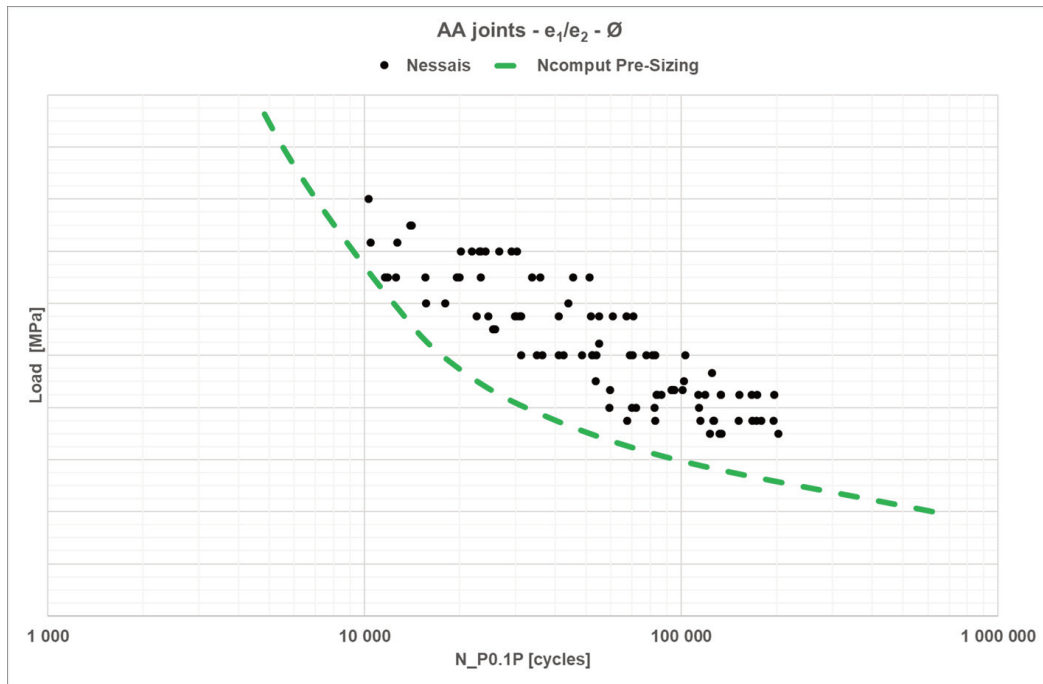


Figure 6. Performance of presizing crack initiation for lap joint.

Structural substantiation methodology

When the development of the aircraft progresses, the sizing evolves and stress engineer have refined Finite Element Models of the parts. The aircraft mass is optimized to improve the range and decrease the fuel consumption. Thus, the design has to be substantiated in fatigue with more accuracy. For this, a junction section of crack methodology is built.

As for free edge, the junction section of the methodology is industrial, therefore the inputs have to be easy to determine. The FEM is based on a 2.5D model: the plate is a 2D plate element with transverse shear and the bolt is a 1D specific element developed for fasteners. The stress engineer must mesh the junction respecting specific rules on the finite elements close to the fastener. The computation is an elastic one at the maximum fatigue load. The stress tensors in these near elements and the bearing force are extracted as the input of the methodology. This FEM allows capturing the equilibrium states of the junction and the crack initiation is computed with more accuracy. Figure 7 shows the performance of the methodology.

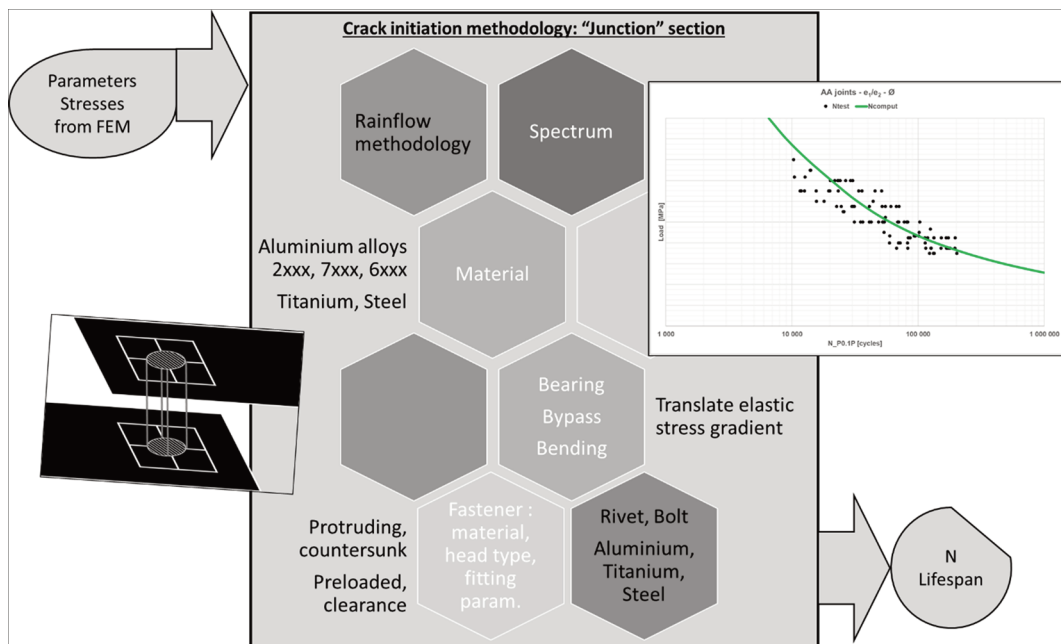


Figure 7. Crack initiation methodology for junction and performance.

State of the art for industrial methodology

The global methodology is empirical: the link between stresses tensor on a simplified FEM and crack initiation on lap joints is established on technological tests. Therefore, a new sizing choice means a new test campaign to validate or tune the actual methodology. The lap joint test is commonly uniaxial test, with basic equilibrium. The structural test is more representative in terms of equilibrium and load applied. For crucial structural nodes of the aircraft, they are performed to validate and secure the final design of the aircraft parts. Industrial methodologies are not well suited to accommodate change or uncertainty in this complex test. Consequently, the associated costs, delays, and risks are significantly high when relying only on the presented methodologies. These observations have prompted the industrial stress office to focus on a localized fatigue approach, with the primary objective of enhancing the ability to anticipate fatigue issues.

DEVELOPMENT OF A ROBUST MULTIAXIAL FATIGUE MODEL

New concept

For industry, the development of a new crack initiation methodology is based on internal experience and studies with academic and scientific partners. The work presented here was carried out with the ONERA, the French Aerospace Lab (Nutte, 2003).

Unlike the global and empirical methodology presented previously, the main goal is to understand and truly represent the physical phenomenon involved in the crack initiation of metallic parts. The idea is to replace the global approach by a local one.

To achieve this objective, the methodology is divided into three steps:

- Characterization of the material's cyclic and fatigue behaviors
- Determination of a reliable fatigue model
- Analysis of a representative FEM

Cyclic and fatigue behaviors

The fatigue behavior of aluminum alloy has already been characterized in an industrial context. The database is available for uniaxial load. Cyclic and multiaxial fatigue behaviors are not common for industry but are crucial to implement a local approach. Therefore, additional tests are conducted in this work to understand and represent the local stress field in the metallic part.

Cyclic uniaxial tests are done on cylindrical specimens, with a constant section length. They are strain monitored and carried out at alternated levels of ε to observe and identify the cyclic hardening mechanisms. The strain is held until the stress is stabilized. The cyclic behavior differs to the monotonic static one as plotted on Figure 8.

Industrial FEM with plasticity are commonly implemented with an isotropic plasticity criterion based on monotonic static tests, because they are often used to substantiate in static cases. However, if plasticity is needed in crack initiation computation, the plasticity criterion has to take into account the cyclic behavior. In this study, a hardening must be implemented in material laws in the FEM.

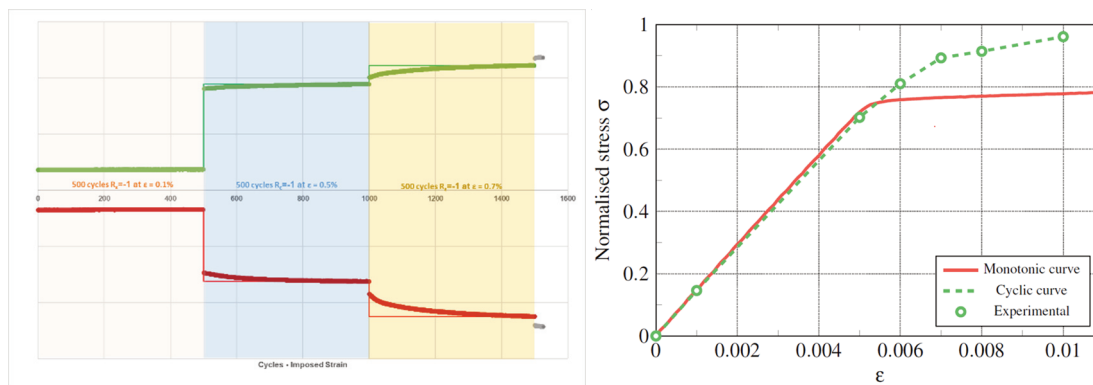


Figure 8. Cyclic behaviour of AA.

In addition, the cyclic behavior exhibits anisotropy in TL (90° with the laminate direction) and 45° from L-TL direction caused by the laminate process of AA. This phenomenon is taken into account in the FEM material definition by Bron criterion (Bron & Besson, 2004), identified in a previous study.

The fatigue behavior of the material is well known in uniaxial load. Data based and complementary test are plotted in Figure 9a. The uniaxial fatigue tests were designed to characterize the fatigue strength of the material together with the influence of the effects of the mean stress. The fatigue tests are stress monitored at various load ratios. The detrimental influence of a positive mean stress ($R_\sigma = 0$) is indisputable compared to a zero mean stress ($R_\sigma = -1$) and a negative mean stress ($R_\sigma = -3$).

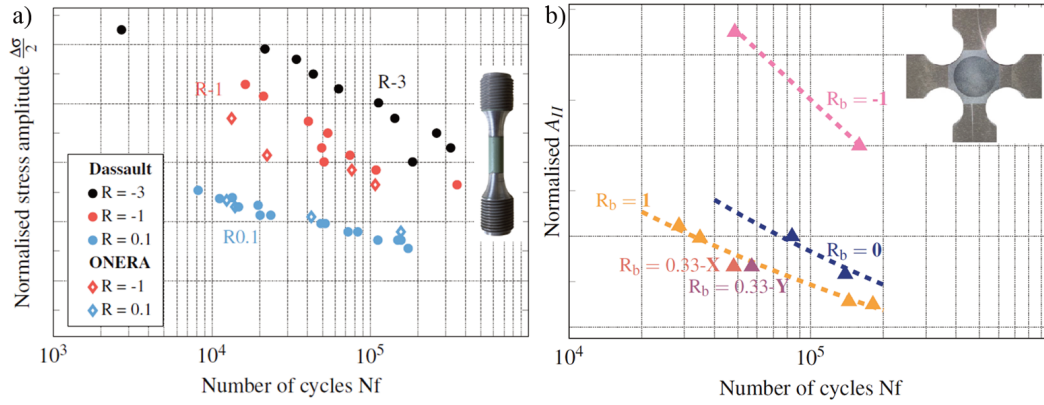


Figure 9. Fatigue tests results a) uniaxial load, b) biaxial load.

Cruciform specimens were defined to evaluate the multiaxial mechanical properties of the alloy. Fatigue tests under biaxial conditions were performed using an available coplanar biaxial testing machine at ONERA laboratory. They enable more extensive loading paths defined by different bi-axiality ratios ($R_b = F_X/F_Y$). Equi-biaxial tests ($R_b = 1$), bi axial tests with ratio 1/3-2/3 ($R_b = 0.33$), shear tests ($R_b = -1$) and uniaxial compensated tests ($R_b = 0$) were then conducted. A multiaxial Wöhler curve, plotting the ordinate as the octahedral shear stress amplitude A_{II} , shows the obtained fatigue lives (Figure 9a).

$$A_{II} = \sqrt{\frac{1}{2} \left[(\sigma_{a-I} - \sigma_{a-II})^2 + (\sigma_{a-II} - \sigma_{a-III})^2 + (\sigma_{a-I} - \sigma_{a-III})^2 \right]} \quad (2)$$

extracted from FE simulations at the most stressed central element

This curve revealed that the fatigue lives of the four biaxial tests align on almost linear curves for each R_b . In the following, the use of these results is done by more relevant $\sigma_I - \sigma_{II}$ diagrams.

Multiaxial fatigue model

A multiaxial fatigue criterion is a mathematical relationship that connects multiaxial stress values to a given fatigue life. This relationship must be predictive for both multiaxial and uniaxial tests. It requires defining an effective multiaxial stress amplitude σ_{eff} used in a Basquin's fatigue law to compute the crack initiation lifetime N_f .

$$\sigma_{\text{eff}} = A_{II} (1 + B_0 \times t_{\text{eq}}) - \sigma_{I_0} \quad (3)$$

$$N_f = \left[\frac{\sigma_{\text{eff}}}{B} \right]^{-\beta} \quad (4)$$

$$t_{\text{eq}} = \frac{\sigma_{\text{max}} - A_{II}}{A_{II}} \quad (5)$$

The parameter t_{eq} is the main component of the invariant-type criteria chosen here. In uniaxial load, t_{eq} depends only of R_σ . Thus, the first step is to determine the material parameters B_0 , σ_{10} , B et β on uniaxial load tests. Parameters allow capturing the mean stress effect seen on the test database. The results of the identification is plotted on Figure 10a.

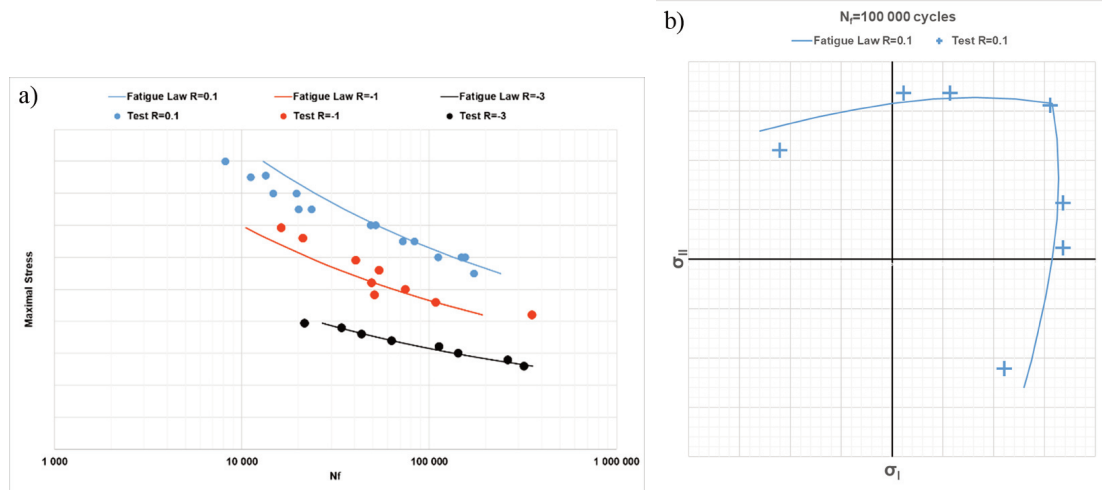


Figure 10. Fatigue tests results a) uniaxial load, b) biaxial load.

The choice of invariant stress is based on biaxial tests. Famous t_{eq} are Sines or Crossland criteria. For AA studied here, Gonçalves et al. (2005) criterion is used because the shape better matches with tests as it is shown on the $\sigma_I - \sigma_{II}$ diagram for $N_f = 100\,000$ cycles $R = 0.1$ (Figure 10b). A key distinction of the Gonçalves criterion is its reliance on the maximum principal stress, whereas the Sines and Crossland criteria primarily depend on the trace of the stress tensor. This fundamental difference may explain why this criterion performs better on the multiaxial fatigue for this alloy.

At the end, the Gonçalves-Basquin law predicts lifetime with good accuracy on uniaxial and multi-axial, test database (Figure 11).

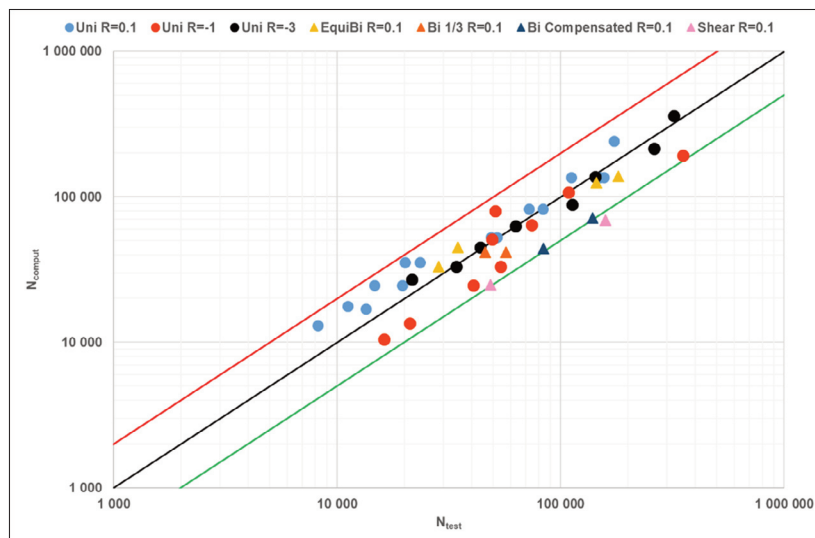


Figure 11. Performance of multiaxial fatigue law.

Representative FEM

After a new characterization of the cyclic and fatigue behavior, and identification of a robust fatigue law, the last step focuses on an accurate FE model to obtain a representative local stress field close to the geometrical singularity, which is studied.

As explained before, the material law must be representative of cyclic behavior. Hence, anisotropy and hardening are taken into account in FEM. Then several cycles of constant amplitude load are computed until the stability of the stress field.

For FEM on free edge studies, 2D or 3D refined models have to be generated, depending on the parts. For an assembly, a 3D model is needed, used to apply the initial bolt preload and then repeated cyclic tensile loading. The model consists of sets of solid elements for the plates and another set for the bolt. To simulate the interaction between the bolt and the plate, a set of contact properties was used on the corresponding surfaces. These elements allow transferring the pressure between the contact surfaces.

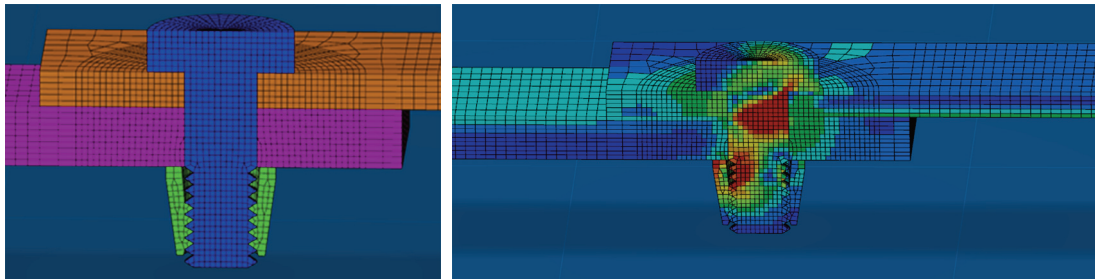


Figure 12. FEM of fastener joint.

Experimental-numerical correlations are performed to ensure the representativeness of the finite element simulations. The choice is made to compare the strain field. Despite the inability to experimentally measure local strains at the hole edge due to the presence of the bolt head, if the visually observable experimental field is comparable to the numerical field, the numerically estimated strain near the fastener hole is also in agreement with that experienced in the specimen during the test.

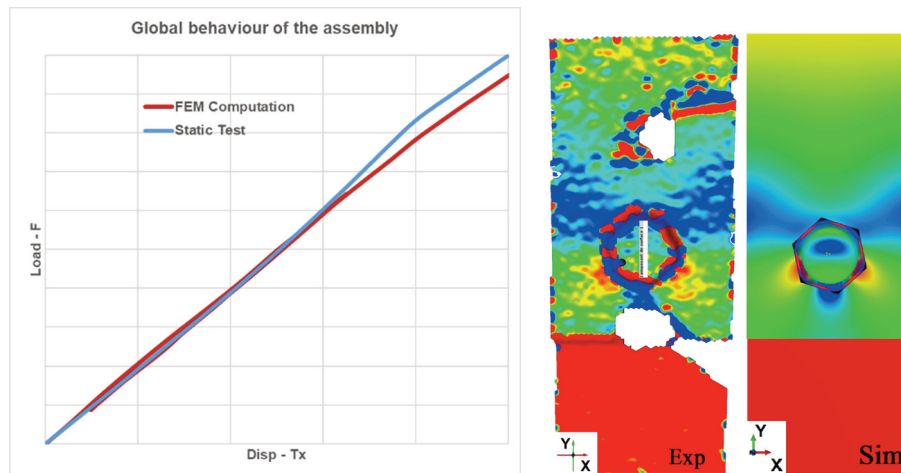


Figure 13. Global and local correlation between test and FEM.

Crack initiation with FEM data

Computed crack initiation on each finite element of the mesh part leads to a severe lifetime because of high level of stress close to the singularity. In this study, stress gradient and volume effects have to be taken into account to post process the FEM in fatigue. Several methodology exist in the literature based on critical length, surface or volume. However, they don't produce good results on free edge and junction tests. The use of probabilistic approach (log-Weibull model (Goulmy, 2017)) has been evaluated with success in (Nutte, 2003).

Junction application

The critical issue of this paper is the application of multiaxial fatigue model on assemblies. Tests have been done with: OS specimen, drilled hole plate with only by pass stress, 1NS specimen, unsupported lap joint with one line of fastener for only transferred stress and 2NS specimen, unsupported lap joint with two lines of fastener, for both of them. These three geometries have been computed and ran with the multiaxial fatigue approach.

The results, plotted Figure 14 accurately represent the location and lifetime of crack initiation for the uniaxial specimen. The industrial methodology also provides good accuracy in these applications, as these tests are commonly used for its identification.

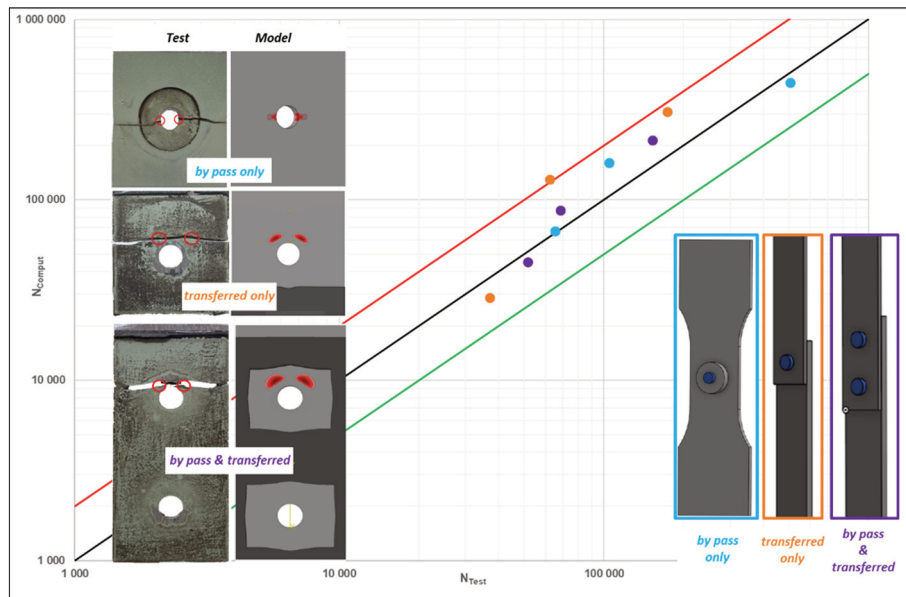


Figure 14. Adequacy model vs. tests on uniaxial lap joint.

The results obtained using the new local approach validate its use on lap joints, which can then be applied to address aircraft-related issues. Particularly, the industrial approach may be found lacking when the location of crack initiation changes due to a multiaxial stress state.

INDUSTRIAL APPLICATIONS

This methodology is relevant for complex areas, where the industrial tools may be non performing and lead to having many conservatism in the crack initiation computation. An example of junction between stringer and frame on military aircraft is presented here. Due to complex load cases, the junction sees bi axial stress field, obviously transferred and by pass stresses in an opposite direction. Specific tests specimens have been designed to represent this equilibrium, called 2x1NS-T fatigue specimens.

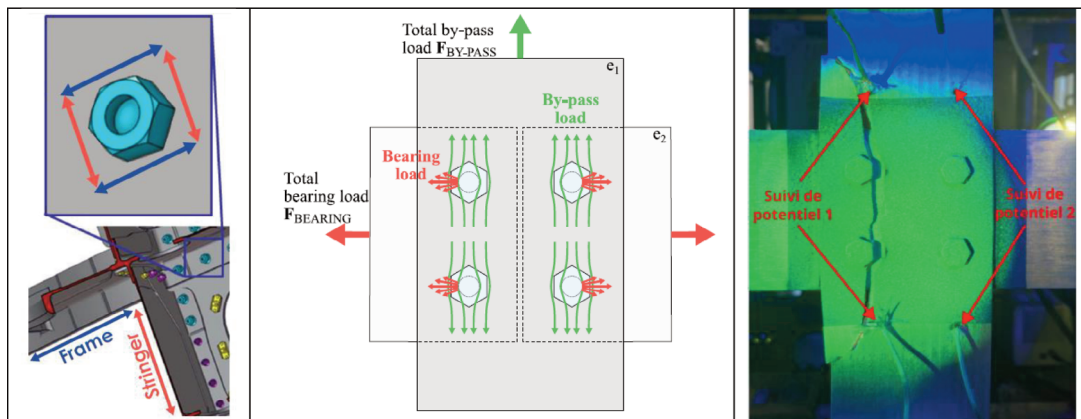


Figure 15. Bi axial fatigue lap joint specimen.

FEM is implemented and solved to compute the crack initiation lifetime and then compared to the fatigue tests results. The representativeness of the simulation has been checked by experimental-numerical correlations. Various biaxiality ratio $R_B = F_{\text{by-pass}}/F_{\text{bearing}}$ between bypass and transferred force have been tested. Experimental observation are detailed in (Nutte et al., 2025).

The ratio drives location and lifetime of the crack. For R_b close to 0, the crack site driven by the by-pass stress, is located at the hole edge, as a net section initiation, similar to that observed in OS structures (uniaxial specimen without transferred load). For R_b reaching 1, the typical crack site is the same as the one for an assembly subjected to a bearing load. Between both, crack sites are less common, resulting from the disorientation of transferred and by-pass loads. The crack initiation site is gradually shifted in the gross section until it reaches the edge of the bolt head.

As shown in Figure 16, the multiaxial fatigue model is predictive for the lifetime and the location of crack. Industrial methodologies enable the identification of the location and lifetime of crack initiation when it is caused by high bypass loads or high transferred loads, respectively. However, it becomes more challenging to maintain accuracy when the equilibrium state lies between these two conditions. These complex innovative tests are a good demonstration of the capability of the model to substantiate with accuracy the crack initiation in metallic parts.

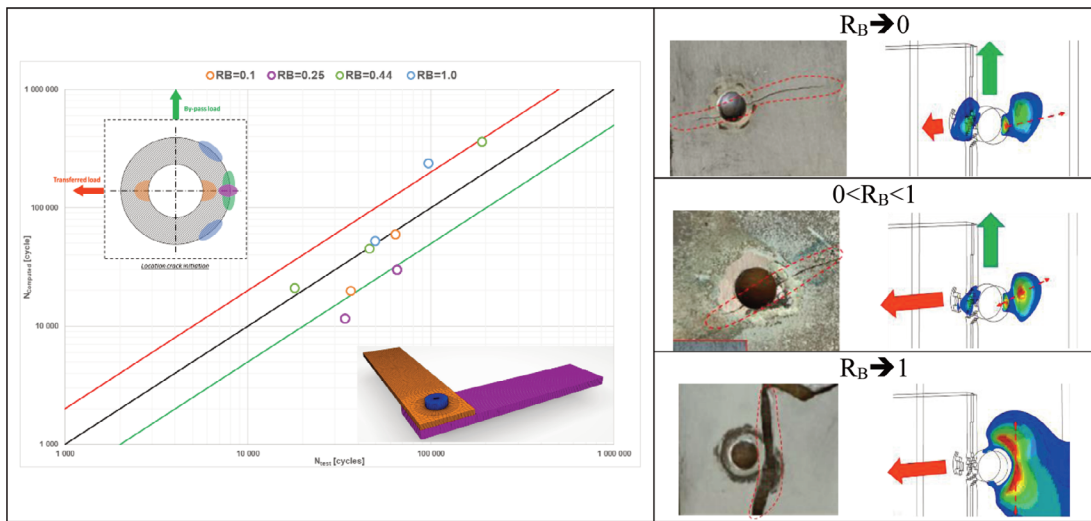


Figure 16. Test results on 2X1NS-T and fatigue computation.

Free edge application

The new crack initiation based on multi-axial fatigue law has to be evaluated on aircraft issues. The first example addressed here is a free edge matter on a Falcon civil aircraft, where the load leads to a high level of bi-axiality. The part is a massive 3D fitting, located on a fuselage and connecting the vertical tail plane.

As described, the new approach requires an accurate FEM and the load has to be very representative to obtain the good stress field on the fitting. The rationale chosen here (Figure 17), is to build a refined FEM of the parts, integrated in a global aircraft section model. That allows having the real computed load applied on the fitting and a major opportunity to obtain a good equilibrium of the parts.

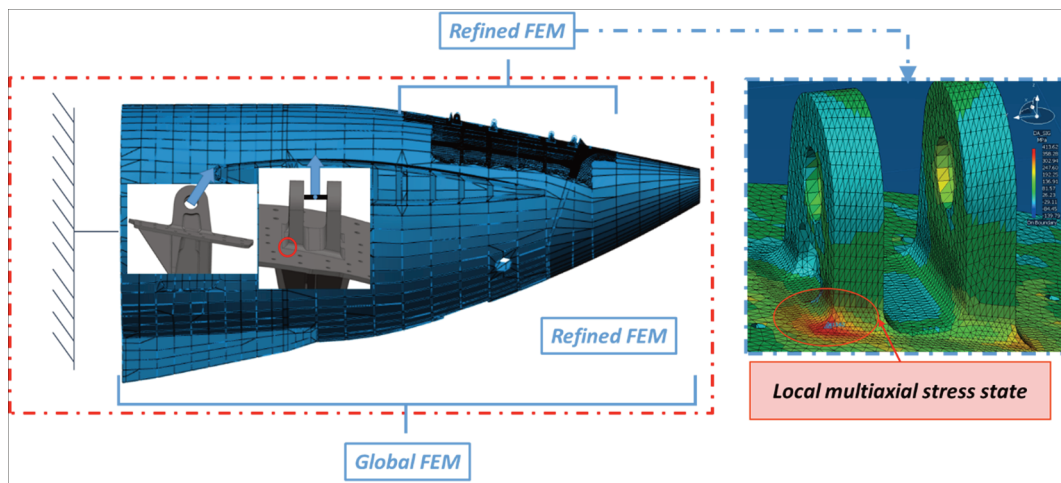


Figure 17. Integrated FEM model for multi-axial fatigue analysis.

The FE computation is done with representative elastoplastic material law identified on the cyclic characterization. The spectrum load fatigue is a $R = 0$ constant amplitude load. The stress ratio σ_{II}/σ_I in the fitting foot is around 0.45, which shows a bi-axiality

stress state. The crack initiation law is thus suitable for the fatigue substantiation of this complex part. The new methodology allows removing conservatism computed with the industrial approach (which prevails for safety in this particular equilibrium). In this case, the computed lifetime is 4 times longer when the multiaxial fatigue approach is used.

CONCLUSION & PROSPECT

To improve industrial fatigue methodology, the intent is to switch from a global to a local approach hence decreasing the dependency to fully representative test campaigns to tune macroscopic parameters and relying on intrinsic material parameters. The implementation of the fatigue multiaxial model is based on three main axes of work: material characterization, fatigue model identification, and local refined FEM.

The new methodology has been implemented and assessed on some representative aircraft applications. The positive results presented here are supportive of continuing these works. Improvements may consist of the following points:

- Development of a cyclic test database to characterize hardening or softening effects, which are crucial for the good accuracy of material laws in FEM.
- Development of a multiaxial test database to identify a precise fatigue model and improve it, by evaluating the stress-strain model and critical plane model.
- Study of scale and gradient effects in more depth, in particular the implementation of a probabilistic approach on aircraft models.
- Spectrum
- Question about the treatment of aircraft issues by the use of a multiscale approach and big data approach to use refined FEM of the aircraft.

For industry, the main goal of developing such methodology is to gain confidence in crack initiation substantiation by a physical approach. This will allow for better targeting in technological and structural tests and optimizing designs with a more robust methodology the structural critical nodes of the aircraft.

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