Probabilistic Fracture Estimate Tool for the Evaluation of DARWIN-3D Code

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Résumé :

Le but de ce papier est d'introduire l'outil de fissuration probabiliste SCILAB-AFGROW. Cet outil a été développé par Safran Landing System (Safran LS) dans le but de vérifier et d'interpréter le logiciel DARWIN-3D. Ce dernier a été développé pour renforcer le processus de tolérance aux dommages sur les composants de moteurs d'avion. Il s'appuie pour le calcul de la probabilité de fissuration sur l'utilisation du modèle éléments finis du composant, d'outils probabilistes ainsi que de courbes d'occurrence de tailles initiales de défauts- très spécifique aux composants moteurs. Les capacités en fissuration probabiliste a été démontré sur deux exemples analytiques : un barreau avec fissure interne elliptique et un cylindre avec fissure surfacique sur la paroi interne.

Abstract:

This paper aims at introducing the SCILAB-AFGROW tool that was developed by Safran Landing Systems (SAFRAN LS) for the sake of performing probabilistic fracture estimates of titanium gear parts. This tool has been successfully used at evaluating the risk of fracture results of the well-known software DARWIN-3D®. The latter has been developed for turbine engine parts and relies on using probabilistic tools, FLIGHT-LIFE crack growth solver and specific exceedance curves. The probabilistic capabilities of SCILAB-AFGROW have been demonstrated by considering two analytic examples: a block with an embedded crack and a hollow pressurized cylinder with a surface crack.

Key Words: Probabilistic, fracture, estimates, crack growth, DARWIN-3D, SCILAB-AFGROW

1 Introduction

This work aims at introducing the probabilistic fracture estimate tool SCILAB-AFGROW that was developed within the Safran LS Research Pre-Project (SLS-RPP) on probabilistic fracture estimates of titanium gear parts. In contrast to titanium alloy engine parts, these probabilistic estimates are today neither compulsory nor recommended by the airworthiness authorities for landing gear systems [1]. As a matter of fact, the crash of the UA232 flight (Sioux City, 1989) has revealed occurrence of Hard-Alpha (HA) anomalies on turbine engine parts that could not be early detected by usual NDT inspection methods [2], [3]. Following this fatal accident, the Federal Aviation Agency (FAA) has issued a strong recommendation requiring the engine manufacturers to enhance the conventional safe-life process by additional *fracture risk assessment* on critical titanium alloy parts. Indeed, while the structural integrity of these Titanium Alloy parts has been fully demonstrated through a conventional design and life process (safe-life), the assessment of anomalies occurrence has not been robustly addressed. The probabilistic fracture estimate process does not replace the existing safe-life methodology, but expands upon it [2].

The risk assessment is usually performed by the engine manufacturer engineers using DARWIN® software [4]. This software has been funded by the FAA and developed by SwRI (Southwest Research Institute) in partnership with General Electric, Honeywell, Pratt & Whitney, and Rolls-Royce. In 2015, the SLS-RPP activities were dedicated to the risk assessment of a 3D new version (V8.2) of DARWIN® [4]-[6]. The fracture risk analysis relies on using probabilistic tools, the deterministic FLIGHT-LIFE crack-growth solver and exceedance curves describing the statistics distribution of the existence and the initial size of the crack. . Its application to a 3D gear component model suffers immediately from memory size problems and inability to support some finite elements type. Moreover some important damage tolerance criteria - such as the verification of the net-section and/or the residual strength - are not considered by the current versions of DARWIN-3D in the computation of the (conditional) probability of fracture. These limitations encouraged SLS-RPP to develop a new tool based on chaining the numerical statistics library freeware SCILAB with the deterministic code AFGROW® (Windows 2000) [1].
The deterministic and probabilistic capabilities of the proposed tool SCILAB-AFGROW have been demonstrated by considering two analytic examples: 1) a titanium block under tensile load with an embedded crack and 2) a hollow pressurized cylinder with a surface crack on the internal wall. The proposed tool has been successfully implemented in a Human Interface Machine (HIM) that is currently used to carefully cross-check and to easily understand the probabilistic fracture estimates computed by DARWIN-3D®. Moreover, it allows the users to correct the computed (conditional) probability of fracture by taking into account the net-section and residual strength criteria. In addition to various variables, SCILAB-AFGROW is also capable to deal with structural random variables and probabilistic sensitivity analyses. The probabilistic sensitivity information is useful in determining the importance of the random variable to the advocated probability-of-fracture estimate [7]. This issue is not addressed herein and will be discussed in a future work. The probabilistic fracture analysis of the block with a Gaussian distribution of the structural width and length variables has been performed using a Monte-Carlo and an Advanced Kriging method [8].

2 Deterministic crack growth

Unlike common deterministic codes such as AFGROW or NASGRO, DARWIN proposes the use of a finite element stress model (2D, 2D-axi and 3D) in order to perform a crack growth analysis. Indeed, the FEM stress model can be imported from ABAQUS and/or NASTRAN to DARWIN as a mesh (UIF) and loading files (UOF) using the FE2NEU FEM Converter tool [4]-[6]. This allows to access directly to the (thickness) stress gradient information. Two crack growth examples presenting analytical stress solutions will be detailed in the following sections.

2.1 Semi-infinite Block with Embedded Crack

The first example consists to use DARWIN-3D to simulate the internal circular crack growth problem of a titanium semi-infinite block under tensile load proposed by DARWIN verification document [6] (figure-1.*a*). The crack growth has been computed using a Paris Law: Kc= 58.7 ksi-in1/2, m=3.87, C= 5.248x10-11. Figure-1.*b* illustrates the crack evolution compared to AFGROW, NASGRO the analytical solutions for different tensile load: 90 ksi, 95 ksi, 100 ksi, 105 ksi and 110ksi.

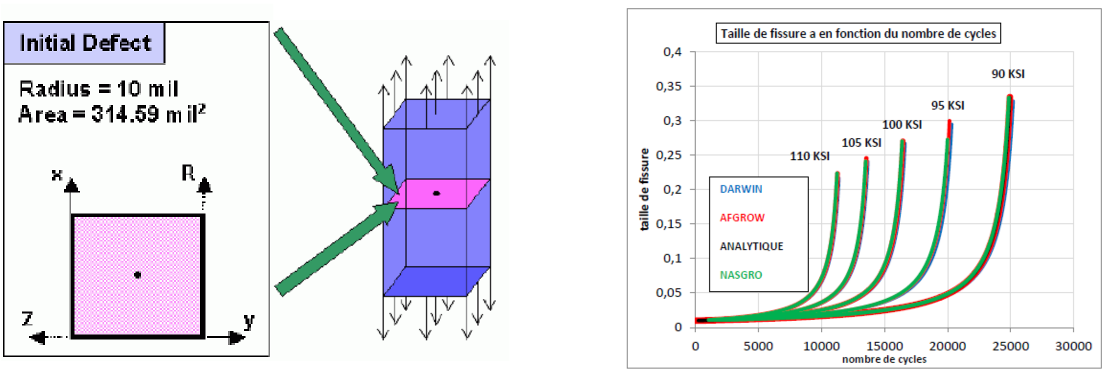

Figure-1: *a*) semi-infinite block under tensile load *b*) Crack size evolution for different stress load.

2.2 Hollow cylinder with internal surface crack

The second example concerns a crack growth of a surface defect located in the internal wall of a hollow pressurized titanium cylinder (figure-2.*a*). The cylinder unit stress (gradients) on the cylinder wall computed using ABAQUS (C3D4 elements) and compared to the analytical solutions are illustrated on figure-2-*b*. For the cracks and zones definition, DARWIN proposes an automatic optimization procedure that could not be unfortunately applied to the cylinder because of the large size of the FEM model. Therefore, the alternative "elementary" manual procedure has been used to prescribe a 0.01" axial surface crack (SC30: ***a***=***c***=0.01") in the internal wall of the cylinder. Let us remind that DARWIN uses a 2D plate model to solve the crack propagation analysis on the 3D cylinder while AFRGROW® proposes an equivalent cylindrical shape model to perform the analysis (figure-2).

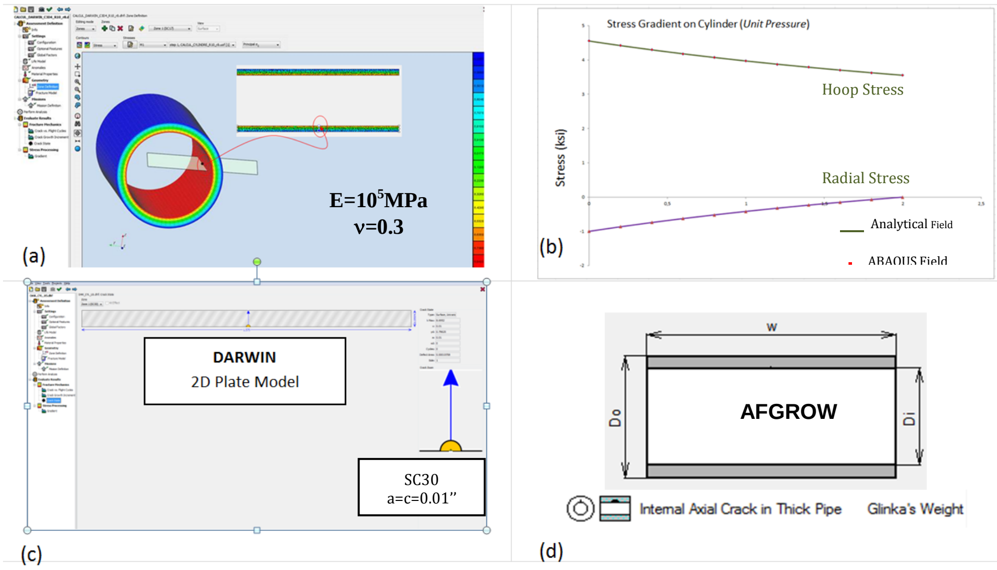

Figure-2: *a*) 3D FEM stress Model imported in DARWIN b) Unit pressure Stress gradient distribution c) DARWIN crack growth 2D-plate (Equivalent) Model d) AFGROW® pipe Model

The Paris law parameters describing crack propagation behavior of the cylinder are summarized in table-1 below:

Table-1: Paris Law parameters

C = 9.87×10^{-10}	**m** = 3	□$\mathbf{K_{th}}$ = 3	$\mathbf{K_c}$ = 58	$\mathbf{K_{ic}}$ = 58

The crack size evolutions ***a*** and ***c*** versus the number of cycles computed by DARWIN® and compared to the ones obtained by AFGROW® are illustrated on figure-3.

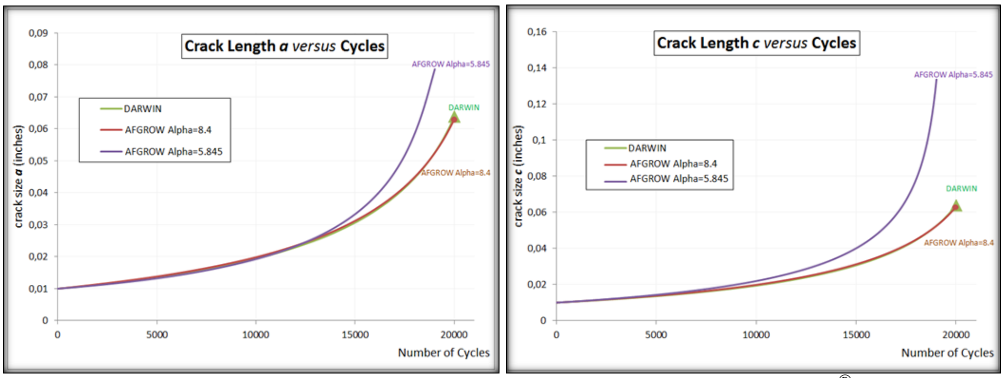

Figure-3: ***a*** and ***c*** crack size growth: DARWIN versus Analytic versus AFGROW® versus NASGRO

3 Risk Assessment of the Cylinder

3.1 Probabilistic Fracture Formulations

The probability of fracture of titanium structure with a volume V is given as follows:

$$P_f = \sum_{i=1}^{m} P_f^c\big|_i P(i) \tag{1}$$

where ***m*** equals the number of zones, P_f^c is the conditional probability having the existence of k anomalies. $P(k)$ is the Poisson density function with an average anomaly occurrence rate α. In the practice, α is a small number (α<<1) the probability of having no defects is $P(k) = P(1), \forall k > 1$, so that :

$$P(k) = \alpha \times e^{-\alpha} \approx \alpha \qquad (\text{for } \alpha << 1) \tag{2}$$

The probability of fracture (4) can be re-written as:

$$P_f \approx P_{f|1} \times P(1) = P_{f|1} \times \alpha e^{-\alpha} \approx P_f^c \times \alpha \tag{3}$$

In the case of a structure with (m) numerous zones of fracture (1 anomaly by zone), the probability of fracture is given as:

$$P_f \approx \sum_{i=1}^{m} P_f^c(i) \times \alpha(i) \tag{4}$$

The anomaly occurrence rate α in a Volume **V** is calculated as [4]:

$$\alpha = N_{Total} \times \frac{V}{W} = N_d(a_{min}) \times \frac{V}{W} \tag{5}$$

The cumulative distribution function (red curve) is expressed as follows (see figure-4.*a*):

$$CDF = 1 - \frac{N_d(a) - N_d(a_{max})}{N_d(a_{min}) - N_d(a_{max})} \tag{6}$$

Different methods are proposed by DARWIN® (Risk Assessment) in order to compute the conditional probability of fracture: Monte-Carlo (MC), LAF (Life Approximation Function) and the importance Sampling methods. Confidence bounds for the probability computation are also proposed. In this work, the conditional risk of fracture will be computed using Monte-Carlo as:

$$P_f^c = \frac{N_f}{N} = \frac{\text{Number of failed samples}}{\text{Total number of sampling}} \tag{7}$$

3.2 DARWIN Risk assessment

The risk assessment of the cylinder has been performed by considering deterministic values for the stress load (65ksi) and the number of cycles (**N**=20000 cycles). The only variability concerns the occurrence and the distribution of the initial size of the surface crack (SC30) which are actually described by the exceedance curve (see figure-4.*a*).

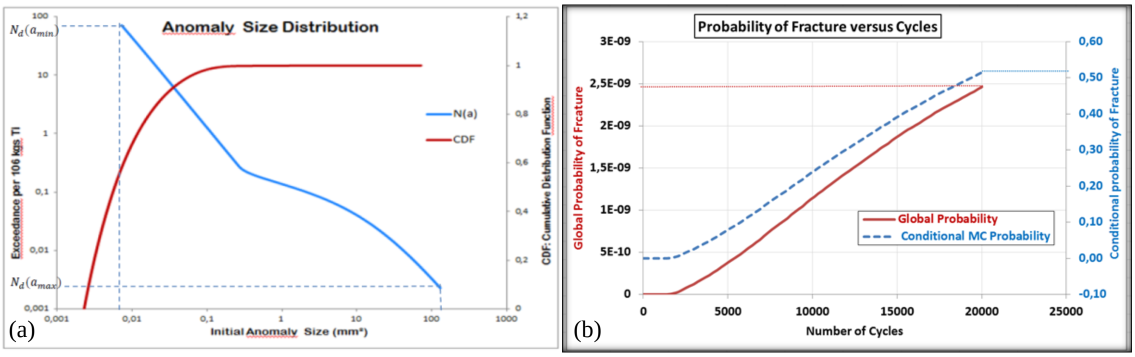

Figure-4 a) Exceedance curve (blue) and its cumulative distribution function (red)
b) Evolution of the global and conditional probability of fracture versus number of cycles

The evolution of the global probability of fracture versus the number of cycles is illustrated on figure-4-*b* ($P_f = 2.5\times10^{-9}$ *@ 20000cycles*). The conditional probability also is given ($P_f^c = 0.5$ *@ 20000cycles*). The occurrence rate is given by equation (5) and corresponds to a value of $\alpha = 4.78\times10^{-9}$.

The evaluation of these probabilities will be performed in the next paragraph thanks to the SCILAB-AFGROW probabilistic fracture tool developed and proposed in this work.

3.3 SCILAB- AFGROW Risk Assessment

A new tool has been developed based on the interfacing of ABAQUS®, the AFGROW® VBA COM (Excel) Server functionalities and the numerical statistics library SCILAB® (see figure-5.*a*). The application of this tool to the cylinder leads to probabilistic fracture estimates that correlate closely the ones computed with DARWIN® Risk assessment code (see figure-5.*b*).

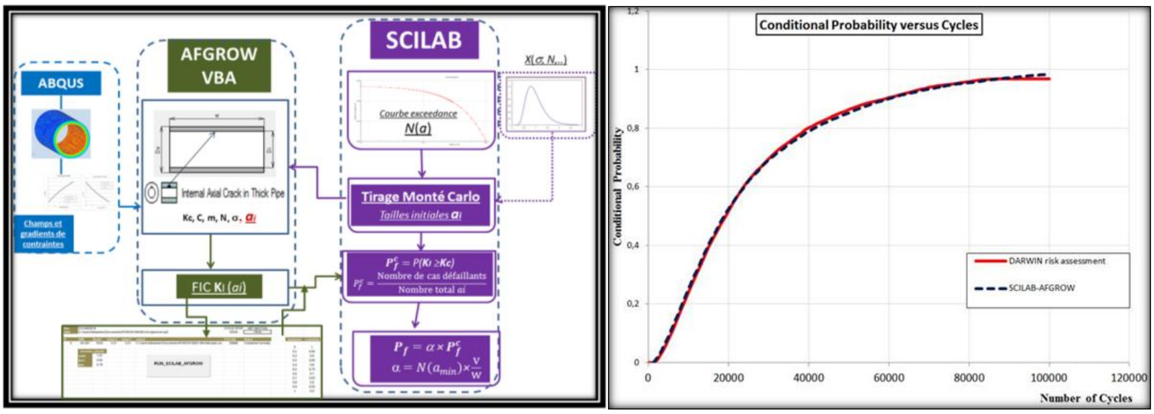

Figure-5: a) SCILAB-AFGROW tool with its VBA (COM Server) MACRO, b) evolution of the probability of fracture (SCILAB-AFGROW versus DARWIN®).

One of the main objectives of developing SCILAB-AFGROW is to efficiently cross-check and to easily understand the probabilistic fracture estimates provided by DARWIN®. Also, the tool proposes to improve these estimates in the case where limitations are observed. One important improvement for Safran LS would be to link SCILAB-AFGROW to 3D crack growth deterministic solvers that are suitable with 3D gear complex geometries. Another improvement may concern the use of the Net Section Criterion (NSC) which is not considered by DARWIN® in the computation of the conditional probability of fracture. As a matter of fact, the crack growth computations in the current versions of DARWIN continue to progress as long as $K_I<Kc$ whether the structure yields or not. Let us notice that this criterion will particularly impact the value of the conditional probability of fracture.

Hereafter an illustration of how (SCILAB) AFRGOW® Net Section criterion is activated within the proposed tool in order to compute the conditional fracture estimate of the cylinder. Figure-6 shows the evolution of the conditional probability of fracture computed by SCILAB-AFGROW (with and without NSC) against the one calculated by DARWIN (without NSC). At target 20000 cycles, the probability P_f^c computed by DARWIN is about 0.53 while the corrected value by SCILAB-AFGROW (with NSC) is about 0.61.

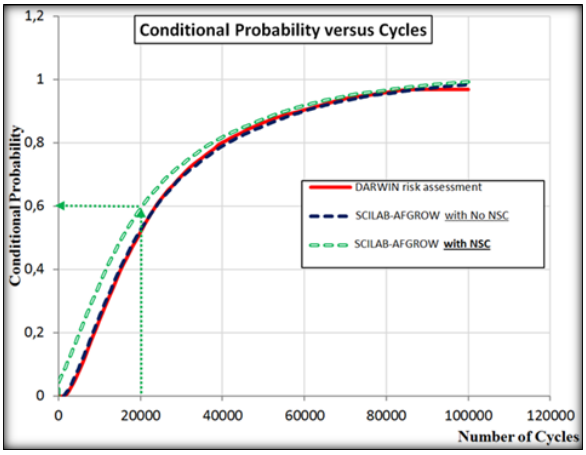

Figure-6: SCILAB-AFGROW correction of the conditional probability computed by DARWIN

In addition to various variables, SCILAB-AFGROW is able to deal with structural random variables and probabilistic sensitivity analyses. The latter information is useful in determining the importance of the random variable to the advocated probability-of-fracture estimate [6]. This issue is not addressed herein and will be discussed in a future work. Hence, Gaussian distribution of the structural variables (width and length) of the block example (§3.1) is considered in the following limit state:

$$\mathbf{g}(\boldsymbol{a}, \boldsymbol{\sigma}, \mathbf{N}, \boldsymbol{d}) = K_c - K_{eq} \leq 0 \qquad (8)$$

where:

a is the crack size described by a uniform anomaly distribution (exceedance curve – figure-7),
σ is a lognormally distributed stress with mean value of 95.4ksi and COV=5%,
N is a Gaussian distributed life scatter with mean value of 20000 cycles and COV = 10%
d is a structural random vector defined by a **width** and **length** following Gaussian distribution with mean value of 100” and COV = 5%

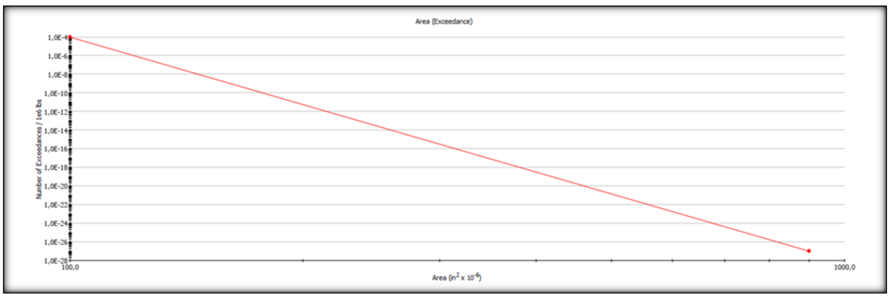

Figure-7: Exceedance occurrence curve with a uniform anomaly distribution

The Fracture probability estimates and corresponding confidence bounds obtained using a Monte Carlo 500 sampling are given in table-2 below. These probabilities are successfully compared to the estimates obtained by using an Advanced Kriging method (25 AFGROW computations) [8].

Table-2: Fracture probability estimate and confidence bounds for the semi-infinite Block

	Fracture Estimate $P_{f\|d}$ / $P_f = P_{f\|d}P_d$	**Low Bound @ 5%** $P_{f\|d}$ / $P_f = P_{f\|d}P_d$	**Upper Bound @ 95%** $P_{f\|d}$ / $P_f = P_{f\|d}P_d$
SCILAB-AFGROW Monte Carlo (500 Sampling)	**0,598** / **$0{,}96\times10^{-5}$**	0,561 / $0{,}90\times10^{-5}$	0,634 / $1{,}02\times10^{-5}$
SCILAB-AFGROW AK-MCS Method (25 calculus) 100000 points ranking	**0,569** / **$0{,}92\times10^{-5}$**	0,567 / $0{,}91\times10^{-5}$	0,572 / $0{,}92\times10^{-5}$

4 Conclusions

A new in-house code SCILAB-AFGROW has been developed by Safran LS and used to perform the probabilistic fracture estimates. The computed probabilities have been successfully compared to the ones provided by DARWIN on two simple analytic examples. The ability of the code to deal with structural variables and to implement robust statistics methods - *such as Advanced Kriging method* - has also been demonstrated. Additional abilities such as the use of probabilistic sensitivities and the implementation of 3D crack growth solvers have been pointed out.

5 Références

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