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DEFFI project for a new concept of fatigue design in the aerospace domain

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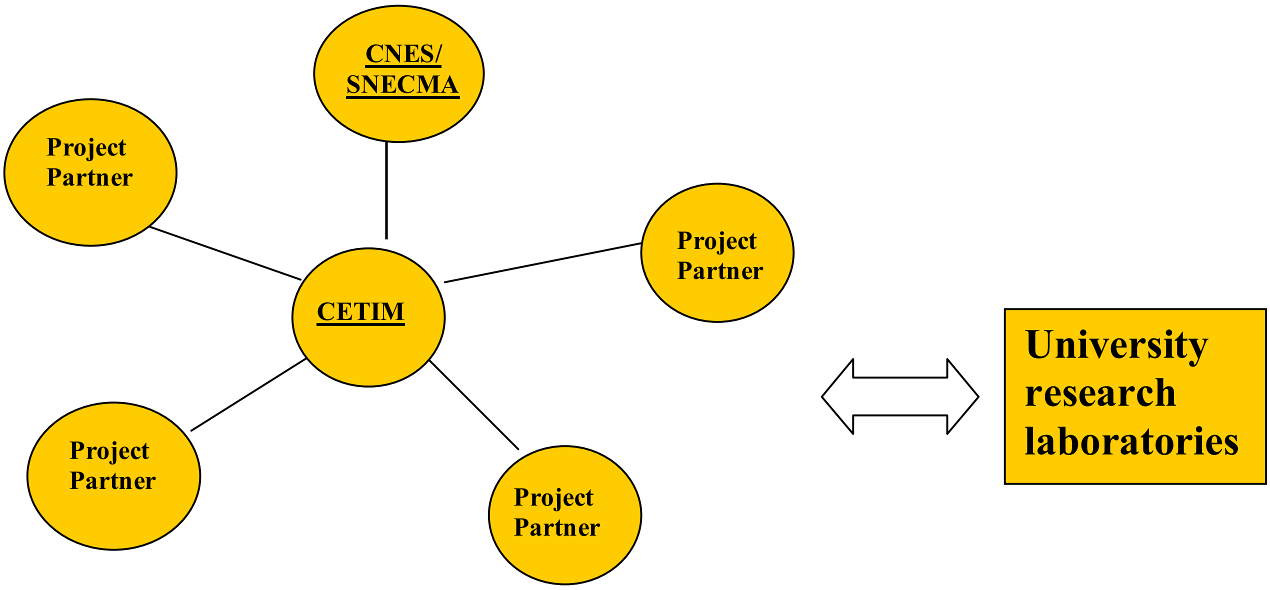
The DEFFI project run by Cetim is an ongoing French national project whose purpose is to promote the development of industrial stochastic methods and tools for mechanical fatigue design. Thus, this paper aims at achieving the necessary results to validate a reliable probabilistic analytical design approach for fatigue in the aerospace domain, as well as demonstrating the platform tools' validation relevance. As aerospace partners of the project, in 2006 CNES and SNECMA began to study with CETIM the case of a rocket engine structure called "blade support", using a simplified but nonetheless realistic model shape. The reliability approach described in this paper is based on the "Stress-Strength" theory where the criterion for acceptability complies with a reliability objective, *i.e.* with the maximum failure probability required in this study. Concerning the analysis of the Stress and loads, the European rocket flights' data base was used and a loading mix strategy was adopted. The launcher mission profile consists of "elementary situations of life" which depend on flight parameters such as velocity, launcher behaviour, aerodynamic loads, the launcher's trajectory deviations, etc. At the end, the reliable Stress distribution curve was calculated. As for the Strength, the structure's material and fabrication were analysed with a sufficient number of fatigue tests up to failure on representative specimens and on components. Reliable fatigue life curves were developed based on these experimental fatigue data tests on the one hand, and on sensitivity analysis performed on the model and material law on the other hand. All these results were achieved thanks to the platform tools which afforded technical support to this case study. Finally, the estimation of the "blade support" structure failure rate was calculated, enabling a comparison to the previously defined reliability objective. The result fulfilled the requirements of the acceptability criterion. The use of a reliable probabilistic approach for the fatigue design in the aerospace domain has been demonstrated but further investigations on load damage structure life are necessary. It is a must to have good understanding of the physical environment and the life of the product, from its manufacturing to its operational use. This non-deterministic approach can help the traditional design approach and can also provide better management of uncertainties and risks. A first step could be the use of this method to make acceptance files for waivers in production. The next objectives are:

- **to obtain the necessary changes in know-how in order to manage industrial projects by mastering their technical risks,**
- **to create an engineering probabilistic culture and a team spirit,**
- **to develop adapted tools for industrial applications.**

I. Introduction

The DEFFI project is a French national project whose purpose is to promote the development of industrial stochastic methods and tools for fatigue design [1]. It aims at designing structures in a lighter, safer and cheaper way than with the usual deterministic approach, while demonstrating the feasibility, the performances and the reliability of a non-Deterministic industrial approach. The project was launched at the end of 2006 and is currently ongoing. Important mechanical, transport and automotive industries are partners of this project - such as SNECMA joined by CNES for the aerospace sector - as well as Universities and CETIM. The traditional deterministic approach for fatigue design is based on specifications where loads and safety factors are given and where designers must meet mechanical and functional specifications. This conservative approach covers the hardware's whole potential service life (excluding unexpected events). It works successfully but may lead to oversized final hardware. So there is a need to design and manufacture hardware preventing the risk of oversizing, especially in the aerospace sector where the lighter the components are, the better the launcher will be. That is the origin of this project [1]. Under the project management of CETIM, each DEFFI industrial partner brings its own concrete technical case study and benefits from scientific research in acknowledged Universities, as shown on the following diagram. The project aims at achieving the necessary results to validate a reliable probabilistic analytical design approach for fatigue in different industrial domains. Each partner with its specific technical case study, coming from a different sector, has its own particular background but works to reach the common DEFFI project objectives. Each of them has the same aim:

- to demonstrate the approach relevance
- to demonstrate the usefulness of the statistical and probabilistic DEFFI tools and at the same time to develop a software platform for industrial use
- to improve its technical competence in the reliability approach of fatigue design
- to highlight and make the most of the results and their validation
- to provide a competitive advantage



The paper will present how a non-deterministic approach applied to the fatigue design of a rocket engine component has been used with success.

II. Launcher engine structure case study and loading context

SNECMA and CNES have implemented the DEFFI project's objectives in an aerospace case study with the help of CETIM. The case study consists of a space engine structure called "blade support", using a simplified but nonetheless realistic model shape. This structure is shear-loaded by random alternative loading that generates a displacement in its transverse direction. No thermal gradient is considered.

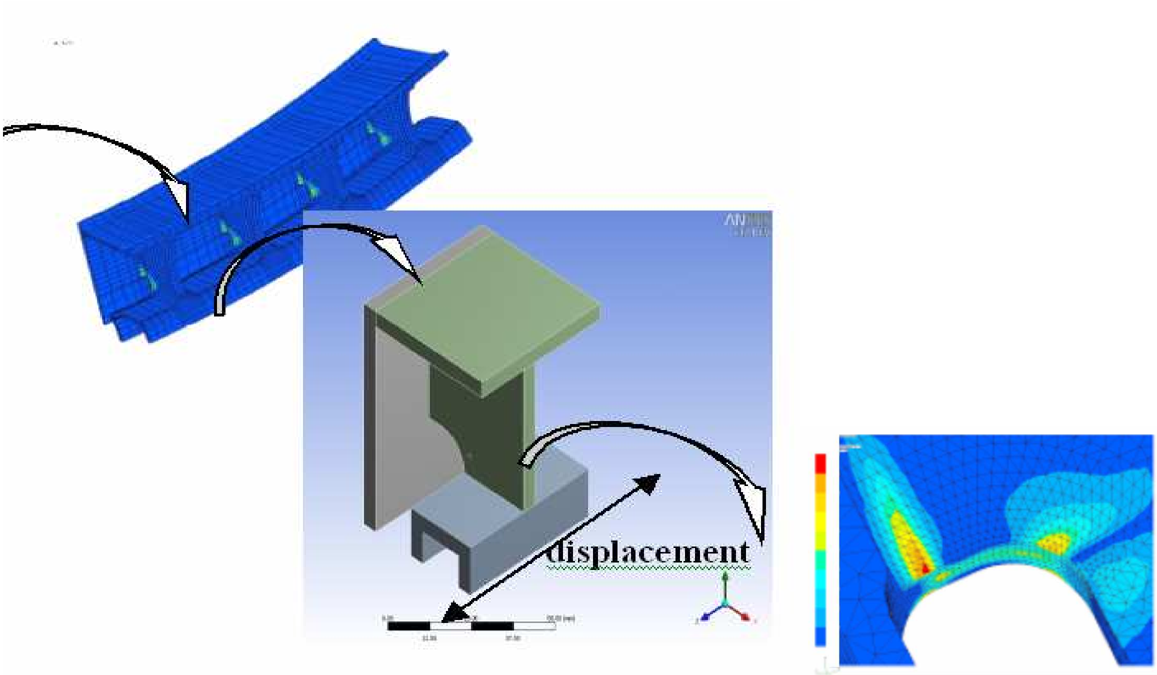


Figure 1. “Blade support”.

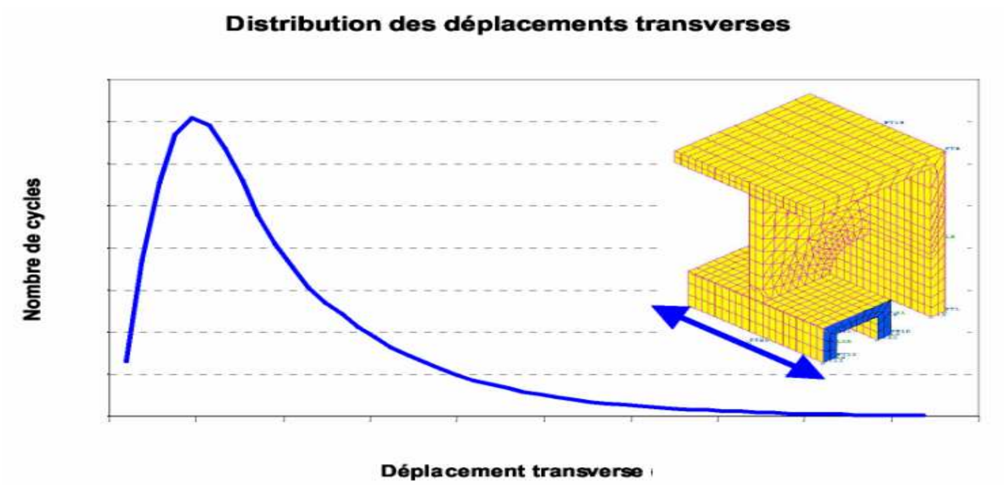


Figure 2. Transverse displacements distribution.

Following several Ariane5 flights, real operational data have been recorded to obtain a realistic time-dependent knowledge of the blade’s displacements. These recordings enabled the analysis of the rocket mission profile distribution. Figure 3 shows a drawing representing the incidence and yawing angles that occur during the launcher’s flight.

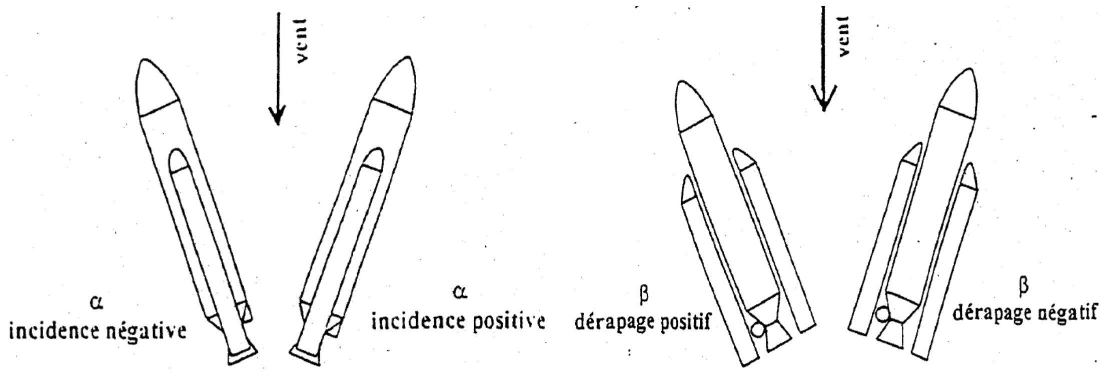


Figure 3. Incidence and yawing angles.

The reliability approach described in this paper is based on the "Stress-Strength" theory.

The stress is the representation of solicitations' variability during the structure's mission. Given a distribution that describes the stress levels experienced in service by a structure and a distribution that describes the strength of this structure (*e.g.* material strength, material properties, design properties, etc.), the analyst can assess the failure rate for this unit, *i.e.* the probability that the stress exceeds the strength:

$$P(x_2 \geq x_1) = \int_0^\infty f_{strength}(x) \cdot R_{stress}(x)dx$$

The relationship between stress, strength and the failure location is represented graphically (*cf.* Figure 4). This graph displays the probability density function of the stress distribution (μ_C,σ_C) and the strength distribution (μ_R,σ_R). Failure occurs when the stress exceeds the strength.

In order to determine the failure probability, we need a way to link stress to the structure's service life and to estimate the probability of failure at each stress level. We can also define the unit's reference load "F_n".

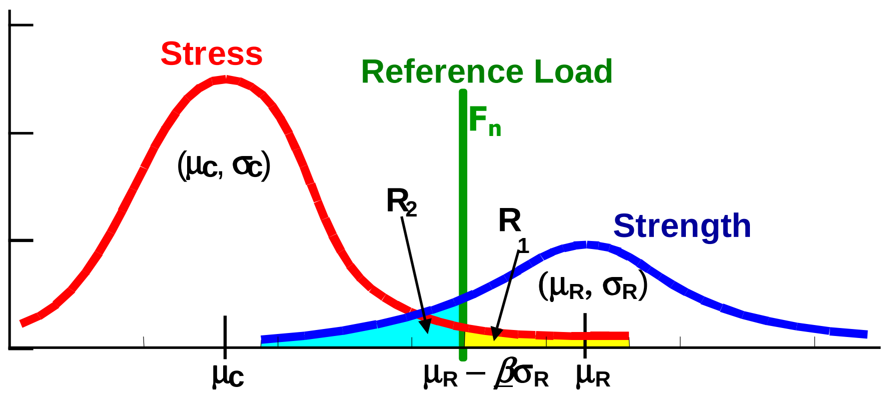


Figure 4. Stress-Strength theory with Load Reference.

According to the methodology implemented within the DEFFI project, the mission's profile consists of "elementary situations of life", depending on flight parameters such as velocity, aerodynamic load, launcher behaviour, rocket trajectory deviations, *etc*. The first step is to master the rocket mission's profile better.

The aim of the rocket mission's analysis is to try to highlight the most important parameters affecting the "blade support"'s life in service. Different parameters were analysed and according to engineers' better judgement, the displacement of the "blade support" was considered as a function of the **incidence** and **yawing** angles, and **velocity** (Mach number).This structure's life analysis is the first step of the fatigue methodology presented here.

The Strength distribution is associated with the material and technological ways of producing the component and usually derives from fatigue tests on elementary structures or on comparable components. To obtain this information, a sufficient number of fatigue rupture tests need to be capitalized on representative specimens, elementary structures or components. The more data is available, the more accurate the estimation will be for the non-dimensional parameter defined for our material /process as the coefficient of variation of the fatigue Strength for a given number of cycles: standard deviation divided per mean value at N_0. This value is relatively constant for a given fabrication; it is a good indicator for the quality of fabrication.

III. Stress part: Mission Profile and mix strategy

To analyse the rocket flights' data, a loading mix strategy is chosen. The "blade support"'s displacement is analysed according to **incidence** (α) and **yawing** (β) angles, and **velocity** (Mach).

Figure 5 gives our chosen strategy as an example:

- The mission is divided into 3 parts according to velocity (0.3-0.5Mach, 0.5-1.5Mach and 1.5-2.5Mach)
- Each of these parts is also divided according to three angular intervals for α and β (9 possible combinations)

Figure 6 presents the displacement for a Launcher flight sequence according to its velocity (life rank between 0.3 and 0.5 Mach) but also to its α and β angles.

The mix strategy produces 27 "elementary situations of life".

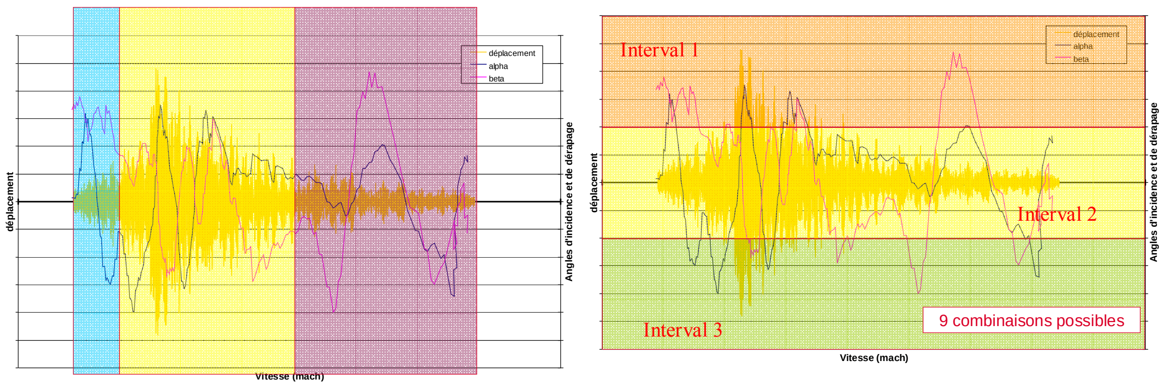


Figure 5. Two examples for division according to velocity, or α and β angles.

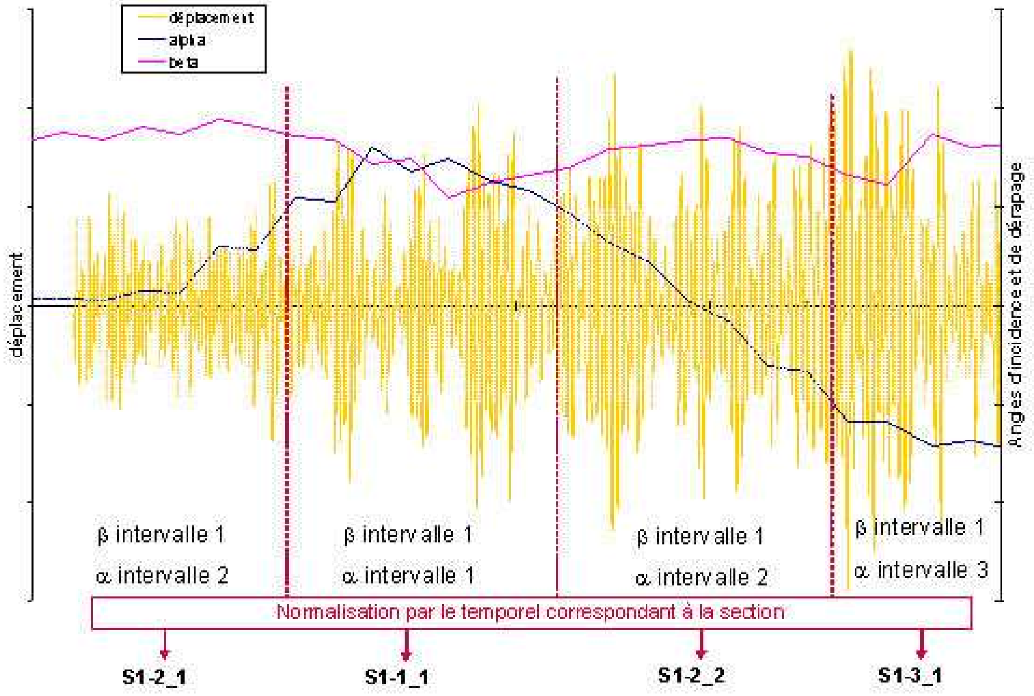


Figure 6. Example of "elementary situations of life" during a particular flight for velocity between 0.3 and 0.5 Mach

1. Data treatment

After choosing the mix strategy and analysing the "blade support" life in detail through the different available flights, 198 files representing the 27 elementary "lives" have been obtained. So the second step is to use the DEFFI software platform to create 198 elementary matrixes and be able to create new virtual flights and obtain the "Stress" distribution curve representing the "blade support" life.

a) The tool named "Quantification-Extraction" enables the quantification of the load signal and the extraction of a representative realistic curve representing:
   - Extreme points extraction (peak and valley)
   - Points quantification from the ranks
   - Information storage in a more compact format

   The time of the acquisition data is mastered according to the signal registered.

b) "Rainflow Counting" is a tool that uses the Rainflow method to count fatigue cycles from the registered signal [2] (see Figure 7).

c) "Equivalent Fatigue" is the platform tool that calculates an equivalent load from the fatigue point of view. The "equivalent fatigue" is a unidirectional constant range load defined by the value F_{eq}, applied a given number of cycles N_0, that produces the same damage than the real flight. [10]. It is calculated according to the Miner rule [3].

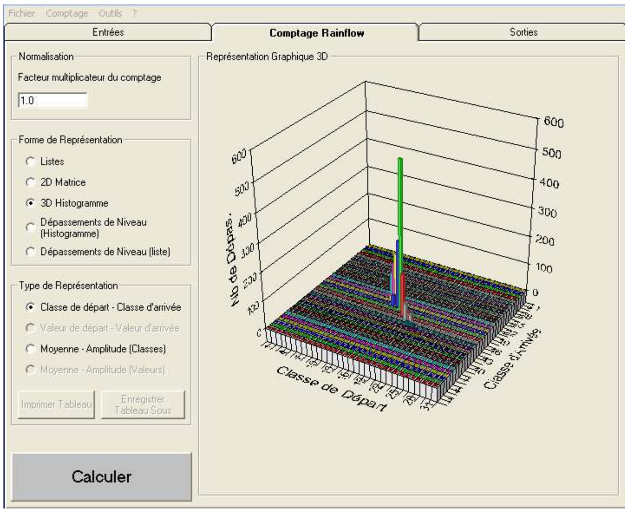


Figure 7. Rainflow tool example data.

2. Stress distribution curve

After the data treatment, for each real or virtual flight an "equivalent fatigue" is calculated for a defined number of cycles. With all flights, a statistic distribution of the load severity applied to the structure is obtained.

Figure 8 illustrates the normal distribution obtained for 100 flights. The mix parameters are defined as follows:

- The first rank : three Mach ranges as defined previously
- The second rank :
  - o $\beta > 1$ is between 0 and 57%
  - o $-1 < \beta < 1$ is between 0 and 27%
  - o $\beta < -1$ is the residual part
- The third rank:
  - o $\alpha > 1$ is between 0 and 63%
  - o $-1 < \alpha < 1$ is between 0 and 10%
  - o $\alpha < -1$ is the residual part

With this distribution, the average of the load severity is obtained with the standard deviation and the coefficient of variation (standard deviation divided by average). The coefficient of variation also known as scattering coefficient is relatively low.

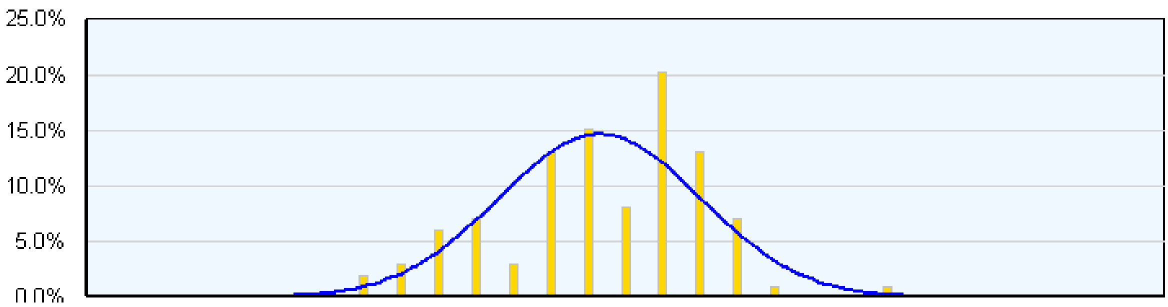


Figure 8. Distribution for 100 flights.

IV. Strength and Quality production

The Strength of the component is defined as a statistical distribution of the fatigue Strength for the number of cycles N_0 used to define the equivalent loading.

As previously specified, it is associated to the material and technological ways of producing the component and is traditionally derived from fatigue tests on elementary structures or on comparable components. This average strength μ_R can be estimated thanks to a sufficient number of fatigue tests up to "failure" on representative specimens, elementary structures or components. The strength scattering σr however needs a larger number of tests, which is generally incompatible with industrial budgets. The capitalization of industrial practices based on similar material and/or processes may help to define the coefficient of variation or relative scattering $COV=\sigma_R/\mu_R=q_R$. The capitalization of q_R represents the quality of fabrication with regards to fatigue damage consequences. As said above, the design problem can be reduced to the identification of the "Strength "distribution [8].

The "strength" information mastering consists in collecting the results coming from different data groups: different materials and production. The aim is to upgrade the strength scattering evaluation for the component produced, in our case the "blade support".

For this study the material data available about our structure was statistically reliable both regarding the material specimens as well as the "blade support". This structure is a forged and machined product made of a nickel alloy. In this case, the low cycle fatigue behaviour is considered.

At the beginning of this study, it was requested to make some choices about important issues:

- to choose a fatigue law
- to choose a reliable material law for the mechanical behaviour to cover the elastic and plastic life of "blade support" material

We decided to use the Chaboche law [4] with some adaptations so that it could apply to elastic and plastic behaviour. The chosen law for fatigue is the Manson-Coffin one [5].

Manson-coffin material data were analyzed considering elastic and plastic behaviour. For each part, the slope of the Basquin line is considered; a linear regression following the equation $\log N = \log C - m.\log \varepsilon$ has been carried out on the results on both elastic and plastic (with N: number of cycles and ε: strain).

Real "blade supports" have been tested with both constant and variable amplitude loading.

The first results were not really consistent because no direct correlation could be found between the material specimens and the structure's test results. The Manson-Coffin law does not seem adapted to the analysis of the "Blade support" case.

In the Stress-Strength approach, the relative scattering of the Stress is defined by a "fatigue equivalent"; a Basquin line is needed with a common slope between the fatigue damage indicator and the solicitation of the force driving this damage.

So it may be assumed that the driving force of the "blade support" damage is a function of the applied displacement. Based on a local plasticity in the "blade support"'s damage zone, the Neuber approximation is used to link the load on the blade support (displacement) with the local strain [6]. The Smith Topper Watson criterion [7] can be proposed to analyse the data.

The material data were analysed with this approach and an identical "Basquin" slope between the blade support and the specimens' test results was found, which allows gathering data after normalisation.

Figure 9 shows a graph with more than 80 results gathering the material specimens' data and the "blade support"'s data.

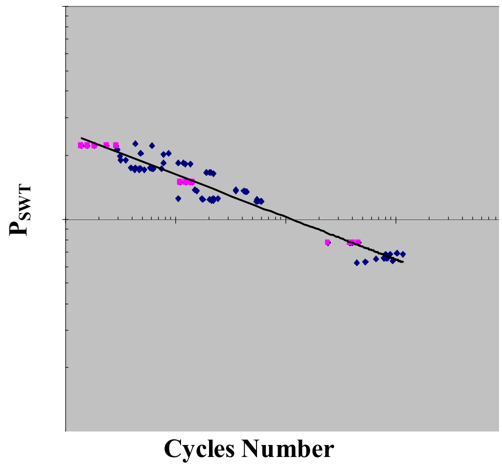


Figure 9. Material results gathering specimens' and blade support's data.

As for the Stress part of the study, the strength distribution curve needs to be calculated at this point. A statistical analysis of the fatigue data was carried out with the DEFFI software platform.

The Strength distribution represents a solution for the design problem, generally speaking. This means that the designer should identify the parameters of the probability density function of the strength. The relative scattering or "coefficient of variation" COV=σ_R/μ_R has been defined for the 15 results on the "blade support" but also for the 80 results regrouping material specimens' data and "blade support"'s data.

V. Acceptance Criterion choice

As figure 4 shows, an Acceptance Criterion or customer reference (generally speaking) must be chosen. In other words, which failure probability do we need and with which confidence level?

The usual risk management rules used in the European aerospace industry are taken into account.

Therefore, we introduced an acceptable objective concerning this mechanical part consisting in a Failure probability no higher than 10^{-6}, associated with a confidence level of 90%.

The "Abaque" tool can calculate the Acceptance Criterion necessary to meet the failure probability requirement.

To use this tool, we need to identify a Reference severity criterion, a reference load F_n, and make an assumption on the severity. In this case, we considered the 99th percentile in terms of flight severity, meaning: $\mu_C = F_n + \underline{\alpha}\,\sigma_C$. In this case, severity defined as 1/100 gives $\underline{\alpha}$ equal to 2,37.

The target is a failure probability of 10^{-6} with a 90%confidence level.

The Acceptance Criterion takes into account the "Strength" distribution's average, fabrication scattering and the scattering coefficient estimated with the available test results. Thus, it is possible to write:

$$\mu_R = F_n + \underline{\beta}\,\sigma_R$$

$\underline{\beta}$ is dependent on the failure probability P_f, on the reference severity criterion F_n, on N the number of units tested to define σ_R and the confidence level γ. Introducing $\sigma_R = q_R.\ \mu_R$, the sample size for the statistical analysis is linked to gathered data from capitalization on the Strength distribution

Figure 10 shows the result found for the "Blade support". In this particular case the "Abaque" tool identifies the coefficient of variation for the Strength, as a function of m*. The m* is the parameter that can be defined by the designer to achieve the failure rate objective, according to the number of available results (here 15). It is defined as the Strength average divided by the reference severity criterion: $m^* = \mu_r/F_n$

Now, for a failure probability of 10^{-6} with a 90% confidence level, it is possible to calculate the Acceptance Criterion thanks to the product $\beta\sigma_r$ and to draw on the same graph the Stress and Strength respective distribution curves (*cf.* figure 11). In order to guarantee failure rate lower than 10^{-6}, the $\beta\sigma_r$ and the minimal average μ_r for the strength distribution can be red in figure 11. Given the observed average for the strength distribution, the failure rate was calculated as 10^{-7} associated with a 90% confidence level. The failure probability *Pf* is given by the risk that a severe use would meet a too weak component *(STRESS > STRENGTH)*.[10]

The random variable $Z = h(z) - g(z)$ also follows a normal law defined by $\mu_z=\mu_r - \mu_c$ and $\sigma z = \sqrt{\sigma_R^2 + \sigma_C^2}$

$$P_f = \mathrm{Prob}(z<0) = \mathrm{Prob}\left(u < -\frac{\mu_Z}{\sigma_Z}\right) = \frac{1}{2\pi}\int_{-\infty}^{\frac{\mu_Z}{\sigma_Z}} \exp\left(\frac{x^2}{2}\right)dx$$

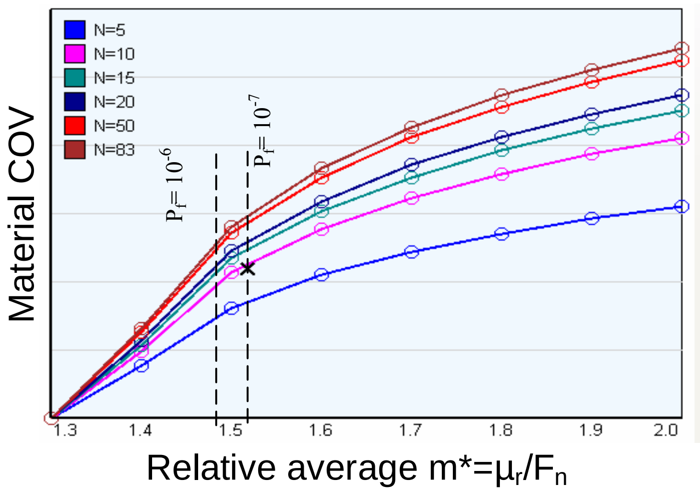


Figure 10. Abaque tool from "blade support" case study.

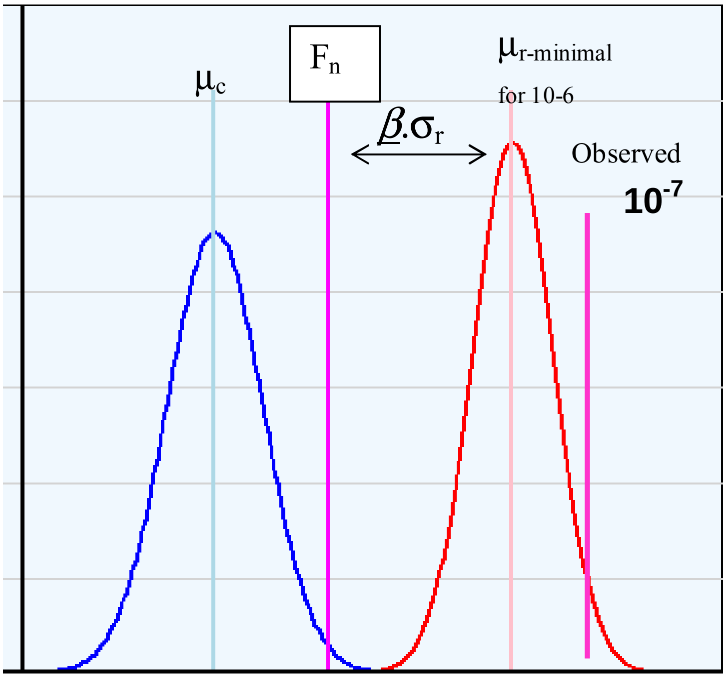


Figure 11. Stress and Strength distribution curve with the Acceptance Criterion: minimal (failure rate < 10^{-6}, , 90% CL) and observed (failure rate < 10^{-7}, 90% CL)

VI. Final Study Results and Conclusions

The main target of Cnes/Snecma is to obtain a reliable approach in order to predict the loading life of the product and its failure rate better. A rocket engine's structure has been studied in an innovative way, focussing on the mission's success, which is typical of our design philosophy.

The case study involves three main stochastic variables which are:

- The model shape
- The loads
- The product material

A parametric finite element model is used in conjunction with an elastic-plastic cyclic material law to determine the local 3D stress and strain fields as a function of the transverse displacement. Reliable fatigue life curves are developed based on experimental fatigue data coming from sample tests and from component tests on the one hand, and from sensitivity analyses performed on the model and material law on the other hand. Thanks to the DEFFI software platform all these steps were conducted with a reliable result, in order to reach the set target: the failure rate objective associated with a given confidence level.

Based on different assumptions and analyses of the Stress distribution and Strength distribution, and considering the Stress-Strength approach as our reliability approach in fatigue design, a failure probability order of $\mathbf{10^{-7}}$ (90% Confidence Level) is obtained for the "Blade support".

This final failure probability result is somewhat lower than required. Indeed, some technical conclusions can be drawn:

- The observed launcher flights were rather calm
- The launcher flights data base must be updated to take possible severe flights into account
- The number of the launcher flights must be increased to improve the reliability of the "Stress" distribution.

Other conclusions concern the use of the DEFFI platform that proved its reliability and validity in this case study. Taking into account that the DEFFI project is ongoing, we are waiting for other results which will come from the other DEFFI partners. The software platform developed in the project will create the condition of success in the application of the Stress-Strength Interference method in the mechanical industry.

Some technical economic studies are ongoing and the results cannot be presented yet. Although they are still being assessed and validated, we can anticipate that the early results are promising as they show real savings in the development and production costs. Not only this rocket engine case study but also other DEFFI partners' results will be precious.

The ambition of the engine structure "Blade support" study was to introduce a probabilistic approach for the fatigue dimensioning field to CNES's and SNECMA's designers. The results can help to turn what was an ambition into reality. For this reason the DEFFI project for CNES and SNECMA will be extended in order to justify a generalization of probabilistic approaches in aerospace designs.

VII. Next Step in the Cnes/Snecma technical case

The aerospace technical case that has been presented in the paper by Cnes/Snecma and CETIM is still under study and like the whole DEFFI project will end during the year 2009. CNES and SNECMA wish to continue working on this technique thanks to the experience and technical help of CETIM. The current results and validations are promising. It will be very interesting to unify all verifications, results, validations and experiences of all DEFFI project partners in order to provide a methodology that can be used in different industrial sectors. It may be said that a good understanding of the physical environment and product's life from its manufacturing to its operational use is a must. The non-deterministic approach cannot only help the traditional approach but can also provide a more efficient management of uncertainties and risks during the production phase. Therefore, the statistical tools and the statistical use of data represent a major step towards the initiation of a non-deterministic approach. From an industrial point of view the technical-economic results are a key point for the success of this probabilistic approach. Besides, all the DEFFI tools were tested in this European aerospace case study, and their reliability will be demonstrated thanks to the results of all the other DEFFI industrial partners. As a result, the software platform gathering these tools will prove useful in the management of uncertainty and will be of great assistance in fatigue design and design to cost strategies.

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