APPLICATION IN THE INDUSTRY OF THE RELIABILITY APPROACH IN FATIGUE DESIGN; A CETIM MULTIPARTNERS PROJECT

André Bignonnet[a], Henri-Paul. Lieurade[b]

[a] a b consulting, 49750 Beaulieu, France
[b] CETIM, 60300 Senlis, France

Abstract. CETIM opened in 2006 a multipartners project named DEFFI: Démarche Fiabiliste de conception en Fatigue pour l'Industrie or Reliability Approach in Fatigue Design for Industry. The project is built on actual components from industrial partners and has the ambition to develop methods and tools to analyse the fatigue failure risk for these different components following the Stress Strength Interference approach. The three main steps are presented:

- the creation of the statistical distribution of the in service loading severity. That is built from calculated or measured data on typical life situations
- the mastering of the fatigue resistance scatter of the products based on a capitalisation strategy of the quality of fabrication.
- the calculation of the failure risk from this information.

This pragmatic approach calls some analysis tools and interpretation in fatigue of the handled information. These tools constitute the bases of a software platform which is developed within the project.
Industrial partners are Cnes, Snecma, Volvo, Mecalac, Pomagalski and SNCF.

1 INTRODUCTION

With regards to the reliability questions in fatigue design, CETIM launches a Great Project on the Approach of Reliable Design in Fatigue, DEFFI: Démarche Fiabiliste de conception en Fatigue pour l'Industrie [1]. On the scientific and technical aspects the topic is indeed at a hinge period. The methods and tools for fatigue design are existing and used in a deterministic way although progress remains to be made in the dissemination of the new methods in the industrial world. On the other hand the evolution of our society claims the zero failure which the current approaches appreciate poorly. Only the reliability methods of design will be able to quantify risks and therefore helps to answer this requirement.

The need in industry for guaranteeing the reliability of the products manufactured and for qualifying the reliability with regard to a definite objective is clear. This opens the way for new scientific and technical developments in particular concerning the problems of durability or resistance to fatigue of the mechanical structures and components.

For technical items the project gives an opportunity to set differently the design problem. That means:

- reflect to the actual life possible situations, its variability, and how to describe it, how and what to measure
- understand how to represent the quality of fabrication linked to the material and processes and how to capitalise this information

The organisation of the project is also describe as well as the difficulties met in industry to open the door of the reliability approaches.

2 STAKES OF THE PROJECT

It becomes obvious that this project must bring a vision, breakdown methods with the practices currently met in the majority of the mechanical engineering. The stake requires crossing a decisive step. Indeed the industrial reasons set that the methods and recommendations resulting from such a project prevail during a score of years.
We will specify the major orientations, which the project must take to reach this ambition according to two axes:

- the numerical simulation in industry
- the culture aspect of reliability

2.1 Evolution of the methods of design and validation

2.1.1 The numerical simulation extended to all industry

The first ingredient which will allow a significant step compared to the current situation is to take into account the fact that in the decade which comes CAD tools and the numerical simulation of the mechanical structures behaviour will have conquered the whole of the mechanical engineering industry, including the SME, and the transfer of know-how of the large companies in the field of the structural analysis towards companies of more modest size is already, or will be, a reality. CETIM, partner of each, registers his action in this direction.

2.1.2 The difficulty of the transfer of know-how in this new context

In a concrete way the difficulties of transmission of know-how are as follows:

- the computer codes in mechanics are accessible to all and the engineering and design departments are able, or will be, to precisely calculate the mechanical fields in any point of the structure. The engineer who was calculated his structure with the usual rules of Resistance of Materials, and used coefficients of correction resulting from the experiment, and specific to the types of products manufactured by his company, does not have any more a reference frame when the detailed numerical simulation gives him precise information on a local scale. He can no longer interpret this information to decide on the acceptance of the structural design. The gained experience is not transmissible any more just as it is; it is necessary to build new reference frames of acceptance of the design adapted to the methods of numerical simulation.

- in the experimental field, the modern test facilities make it possible to reproduce loadings really measured in service or reconstituted using mathematical and statistical methods. Again, with regards to a severised experimental practice and a reference frame of acceptance of the test results builds on experience, the use of loads simulating the reality of the in service loadings requires new strategies of experimentation and of probabilistic interpretation of the results to take into account the diversity of service loadings and the scatter fabrication. The observation of a failure, or not, in a fatigue test does not authorize to validate the level of reliability of the production. The couplings with modelling on the one hand, the characterization of the quality of manufacture on the other hand, are necessary to validate the required level of reliability.

- the difficulty of transmission of the know-how; For much of industry people that will correspond to a real difficulty of transmission of know-how, the richness of the information thus obtained being in complete shift compared to the usual interpretations based on classical engineering calculation approaches and experiments which are supposed severe. It is a significant stake which must make it possible to draw one of the major objectives: take into account the full stress and strain tensor in any point of the structure, interpret these mechanical fields with respect to the fatigue strength and validate the provisional reliability by tightening the bridges between design and validation.

It is thus a question of vulgarisation of the experimental methods of validation coherent with the methods of calculation of provisional reliability used in design.

2.2 The engineering culture of the reliability

Nevertheless the strongest rupture will be on another plan. We will find the stake paramount of this project in new perception that the producer has of his product.

2.2.1 The evolution of the society

Compared to this evolution, the risks on the public image, the play of competition or quite simply the durability of the company push the industry towards:

- a rigour in the working methods: deployment of the engineering system,
- a rigor in the processes of control of the activity: CMMI qualifications (Capability Maturity Model Integration), for example
- a strategy of anticipation of the default risks: development of the operating safety. It is in the heart of this strategy that our project is.

2.2.2 A project to implement the fatigue design reliability method

The stake for the project is to precede or to support industry and to propose fatigue damage risk analysis approaches corresponding to this new vision. It is thus necessary, in the field of fatigue design of the structures, to leave or enrich the deterministic register by climbing the step of the reliability analysis. It is a difficult evolution to make because it corresponds to a major change of thinking in the industry. To precise the delicate points, we can say that the **reliability approach is synonymous with:**

- to quantify the risks, it is necessary to evacuate the coefficients known as safety factor, which too often hide in fact the shades in the knowledge of the product and of its loading,
- to analyse without ambiguity the variety of the loading which will be met in service,
- to calibrate and control the scatter of fabrication to quantify the statistical distribution of the strength which results from this,
- to define the level of risk which one tolerates or the objective of reliability which one sets.

The project will define objectives and deliverables corresponding to these problems, and will integrate professional specificities or regulation aspects when necessary

3 TARGET OF THE PROJECT

Taking into account the context and the stakes described previously the "mission" of the project, in other words the direction of the action and its framework, is synthesized in a sentence:
To introduces into the mechanical engineering industry the methods of reliability in fatigue design and validation for reliable structures and mechanical components. The topic being relatively vast, the perimeter of the project and its limits were defined in the following way**,**

Included fields:
- tools of identification and capitalization of the loadings and their handling for a probabilistic use.
- development of a coherent experimental strategy in the global approach (loading analyses, structural calculation, probabilistic approach).
- quantitative evaluation of the parameters allowing to validate the hypothesis on which is based the probabilistic approach**.**

Excluded fields:
- new developments in static and dynamic structural analysis.
- development of new laws on the behaviour and the damage of materials.

4 STATE OF THE PROJECT

4.1 Organisation of the activities

The project has a cross organisation with in one axis the generic scientific activity and in the other axis the application to the different industrial cases.
The software platform develops the necessary tools for the description of the Stress (the loading and its variability), for the description of the Strength (the fabrication scatter linked to a material process couple), and for the probabilistic analysis from this information. All these tools are gathered in a software platform.
The application to each industrial case includes the organisation of the in service measurement of loads, the capitalisation of the information on the fatigue resistance of the product linked to the fabrication quality, and the calculation of the failure risk. All this information gathered and exploited separately for each case in a Justification and Validation File. This document will be the memory of the project through its application to each industrial case. This represents therefore the know-how acquired in each company.
The entire project documentation is available for partners on a dedicated internet place with confidential areas for each industrial case.

4.2 Software Platform

The software platform is organized around the three main step of the Stress-Strength Interference approach: tools to analyse the variability of the loading in service: the **Stress**, tools to analyse the scatter of the fatigue strength of the components: the **Strength**, tools to analyse the risk of failure and the **reliability** with regards to the fatigue damage. Schematic organisation of the software platform is given Fig 1. Ecole Nationale d'Arts et Métiers (ENSAM-Angers) is involved for all fatigue developments, Institut Français de Mécanique Avancée (IFMA) and Phiméca are involved in statistical and probabilistic developments
Stress : the set of tools which are developed includes

- quantification and classification of the succession of minima and maxima from measured data in service or calculated variation of the loading
- rain flow analysis of these data following the AFNOR recommendation
- tool to mix up rain flow matrix from elementary situation in the life of the component. This tool allows the description of a rain flow matrix which represents a possible life of the component. From a well organized data base it is therefore possible to simulate numerous situations which can be encountered in service.
- rain flow extrapolation
- equivalent loading calculation, based on usual fatigue laws including mean load effect and with a Miner cumulative damage

- statistical analysis of the distribution of the set of equivalent loading that represents the severity of the possible loadings in service
- comparison of populations

Strength

- interpretation of fatigue results following classical fatigue laws
- statistical analysis of the fatigue data, description of the coefficient of variation
- comparison of populations

Risk analysis

- failure probability from different distribution laws of Stress and Strength (normal, log normal, Weibull, Gumbel), taking into account the size of the populations.

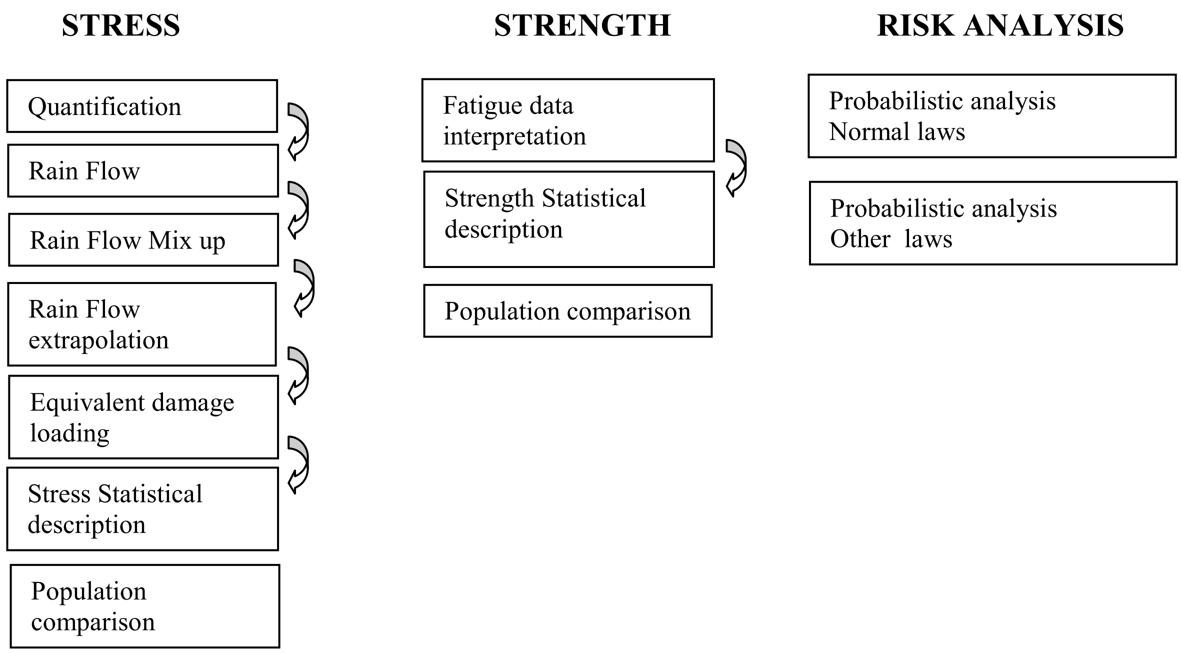

Figure 1 - Tools in the software platform

4.3 Application to industrial cases

Five different cases of application have been decided by the industrial partners:

- a bogie of a TGV
- a seat of cable transportation
- a boom and an arm of earth moving machines
- an element of the Vulcain engine for Ariane 5 launcher

For each application the project uses the platform software to describe the Stress and the Strength, and to perform the risk analysis.

431 Stress

The statistical distribution of the loading represent the Stress (noted S). It is built from a set of measurements in service which are organized in view to generate numerous virtual service lives. To avoid to many temporal measurements, the loading is describe as a combination of two information

- the use of the product: for example in ski lifting cable cars, the type of situation (pylons, station), with different load (empty, half load, full load) or speed (low, high)
- the behaviour of the product: the forces exerted on the structure depends on the condition of operation (wind, repartition of load, ...)

The use of the product: to get more precise description each possible use is described with a proportion of each type of situation. The table 1 shows that each possible use is characterized by the percentages relatives to the crossings/hour for each combination (situation, load, speed). This table gives the proportions v^i_m , c^i_l , s^i_k of hours realized in each situation.

The behavior of the product: that is to integrate the different conditions of life. To that purpose several cable cars are equipped of force gages and they are running in each situation described by the use of the product. The running must be sufficiently wide to be representative of the different conditions of operation (wind, repartition of load, ...). For each crossing j, one obtains a time recording of the forces corresponding to each level of speed **k**, at each level of loading **l** and each situation (pylons, station) **m**. These efforts are condensed in an elementary Rain Flow matrix H^{jklm} normalized to a number of crossings per hour.

m	l	k		Use i			v^i_m (%)	c^i_l (%)	s^i_k(%)	Elementary Matrices H^{jklm} (crossing/hour)
1				% Speed 1			80			j= 1, 2, …, n
	1				% empty crossing			55		
		1 2 3				Support pylon Compression pylon I/O station			68 19 13	H^{111j} H^{112j} H^{113j}
	2				% half load crossing			15		
		1 2 3				Support pylon Compression pylon I/O station			68 19 13	H^{121j} H^{122j} H^{123j}
	3				% full load crossing			30		
		1 2 3				Support pylon Compression pylon I/O station			68 19 13	H^{131j} H^{132j} H^{133j}
2				% Speed 2			20			
	1				% empty crossing			55		
		1 2 3				Support pylon Compression pylon I/O station			68 19 13	H^{211j} H^{212j} H^{213j}
	2				% half load crossing			10		
		1 2 3				Support pylon Compression pylon I/O station			68 19 13	H^{221j} H^{222j} H^{223j}
	3				% full load crossing			35		
		1 2 3				Support pylon Compression pylon I/O station			68 19 13	H^{231j} H^{232j} H^{233j}

Use i : $H^{ij} = N \sum_{klm}[(H^{111j} (0.80*0.55*0.68)+ H^{112j}(0.80*0.55*0.19)+ \ldots)+(H^{211j}(0.20*0.55*0.68)+ \ldots)+\ldots]$
Define for a total life of N hours

Table 1- Description of the use *i* for a given ski lifting line

The extrapolation to virtual life: assuming that use and behavior are independent, one can combine the use of the lines i with the behavior of cable cars j taking the proportion of the elementary matrices. This combination consists in determining the Rain Flow matrix of a given cable car for all its life. This Rain Flow matrix is given as :

$[H^{ij}] = N \sum_{klm} \mathbf{v^i_m\ c^i_l\ s^i_k}[H^{jklm}]$

N is the number of hours for a total life. The whole of combinations that are realized allows generating a population of several hundreds of possible "virtual life" represented by their Rain Flow matrix. For each of these lives one can therefore determine values representative of the fatigue severity. The fatigue severity is usually represented by an equivalent loading of constant amplitude that, repeated a given number cycles, will produce the same damage than the true succession of cycles for the all life of the product; see for example the reference [3]. By simplicity the Stress is define in the following by a normal law defined by a mean value μ_c and a standard deviation σ_c. The distribution of severity of the ski lifting lines can therefore be built. This distribution is usually described by a Normal, a Log normal or a Weibull law. The software operates for the other types of law.

The Design objective is defined for a given level of severity $F_D= \mu_c+\alpha\ \sigma_c$, the coefficient of variation $\sigma_{c/}\ \mu_c$ and the associated level of confidence linked to the size of the sample.

Important comments: This method doesn't necessitate very long and difficult measurements. It can be simply developed as the necessary recordings, once determined the strategy of construction of "virtual life", are rather short. The industrial partners of the project had already more or less what was necessary to apply a good strategy. This is on going.

An other important point is that the values recorded are usually normalized by a characteristic value of the product, the mass of the cable car plus the nominal load in our example, so that they can be used to define the loading on a new product, for example 4, 6, 8 or 10 seat's cable car. Therefore once the first data base is obtained it is not necessary to duplicate measurements to develop a new cable car.

All the software tools which are necessary to establish this **Stress distribution** were developed within the project. They are in the DEFFI software platform.

432 Strength

The Strength (noted R) of the component is defined as the statistical distribution of the fatigue strength, for the life of the product or the number of cycle where the equivalent loading has been defined (see section 331). It is associated to the material and technology uses to fabricate the component and usually derived from fatigue tests on elementary structures or on comparable components. To reach this information a sufficient number of fatigue tests up to "failure" on representative specimens, elementary structures or components. One set of test to failure allows estimating the fatigue strength, and with 5 or 6 testing a reasonable of the mean strength values μ_r is obtained. The estimation of the scatter σ_r needs a larger number of tests which is always incompatible with industrial constraint. The capitalization based on the same material/process may help to define the coefficient of variation or relative scatter $q= \sigma_{r/}\ \mu_r$. The fabricant engages his responsibility on this relative scatter q. It should be verified on the bases of the capitalisation of past information and confirmed a posterior when sufficient fatigue test results can be produced. The capitalisation of q 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 distribution of strength. It means that the designer should identify the parameter of the probability density function of the strength. But the designer who works with virtual design and a few numbers of prototypes has no information on these parameters which would require a production survey. In order to solve this paradox, we have introduced the assumption that the relative scatter $q= \sigma_{r/}\ \mu_r$ is a characteristic of a component family and its fabrication process. Then it can be identified on a similar component, with a statistically relevant number of components tested.
To keep consistent with the customer analysis, one must emphasize that the scatter is measured on the strength dimension rather than on the traditional lifetime. Each experimental lifetime is "dragged" along the damage curve who as the same slope as the damage curve of the material. This qualification of q, $\sigma_{r,}$ μ_r is done at the number of cycle where the equivalent damage fatigue loading is defined as shown in figure 3, with $Neq=10^6$. This manipulation is a part of the software platform. The manipulation of test data is on going.

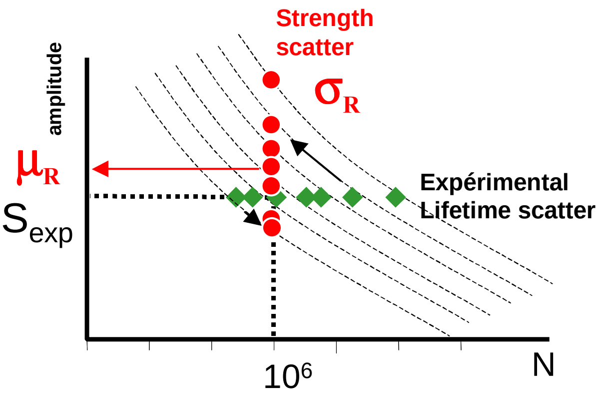

Figure 3: Identification of the parameters of the strength scatter.

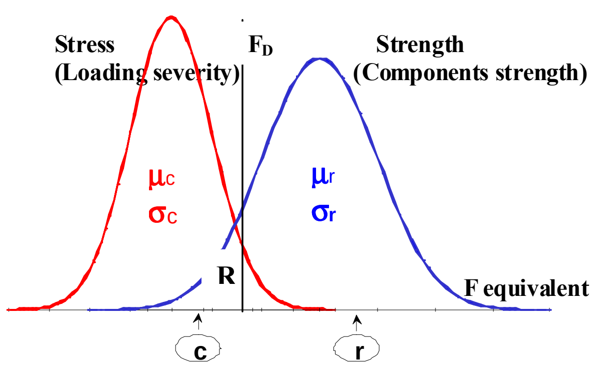

Figure 4: "Stress - Strength" method illustration

Traditional tests have often the objective to verify that a component hold the technical specification. The probabilistic approach need to conduct the test "to failure" (in sense of the functionality) and if possible to perform several tests to get the statistical content.
This approach presents several advantages

- the fatigue strength of the component is estimated, and therefore its potential (can it be used for a more severe application ?)
- a quantitative value is obtained (level of strength) instead of a Boolean information (hold, no hold)

Nevertheless this presents the difficulty to realize several tests. Whilst no miracle method exist, one can mention that the more simple the test (on isolated component), more one can duplicate tests. This will allow validating each key component and to performed synthesis test (heavier, costly, under the pressure of the planning …) on sub systems a priori representative of the production.
It is now indispensable to work on the experimental methods of validation. Indeed, today many so called synthesis tests because they use the whole product but they are not necessarily think for a particular damage mode. Hopefully experience allowed building robust specifications. But when these tests conduct to a failure, it is quite costly and the redesign may be extended to numerous components or does no longer allows reaching cost or mass objectives.

433 Risk analysis

The next step is to give the designers a simple specification and validation procedure. The question is: is the Strength (R) of the component allows supporting the Stress (S) with a given reliability (or with an accepted risk)?

The failure probability P_f is given by the risk that a customer would meet a component too weak for him (S > R). Assuming here that R and S follow a normal law, the random variable Z = R – S also follow a normal law defined by $\mu_Z = \mu_R - \mu_C$ and $\sigma_Z = \sqrt{\sigma_R^2 + \sigma_C^2}$.

$$P_f = \mathbf{Prob}(z < 0) = \mathbf{Prob}\left(u < -\frac{\mu_Z}{\sigma_Z}\right)$$

$$P_f = \frac{1}{2\pi}\int_{-\infty}^{-\frac{\mu_Z}{\sigma_Z}} \mathbf{exp}\left(\frac{x^2}{2}\right)dx$$

This equation shows that the risk is a function of μ_Z/σ_Z , therefore:

$$\frac{\mu_Z}{\sigma_Z} = \frac{\mu_R - \mu_C}{\sqrt{\sigma_R^2 + \sigma_C^2}}$$

The "Strength" parameters μ_R and σ_R are estimated with a confidence level γ by two values m_R and s_R obtained from a limited number of components. Therefore, the risk R depends on the chosen confidence level γ and of the number N of tested components. This is illustrated on Figure 4.

Usually, the number of tested components ($N \geq 8$) allows a reasonable estimation of the mean value. We can accept the assumption that $\mu_R = m_R$ but on the other hand the standard deviation must be corrected by χ^2 :

$$\sigma_r = s_r\sqrt{\frac{\nu}{\chi^2{}_{\gamma(\nu)}}}$$

with $\nu = N - 1$ and $\chi^2{}_{\gamma(\nu)}$, the value for the chosen iso-probability at N-1 d.o.f. If $N = \infty$ then $\sigma_R = s_R$.

The key stone of the method is the introduction of the objective customer F_D at a specific position in the customer distribution. This position is defined by a number α of standard deviations:

$$F_D = \mu_C + \alpha\sigma_C$$

since m_R and s_R are homogeneous to the applied Forces and they can be normalized by the testing reference : $m_R^* = \dfrac{m_R}{F_n}$ and $\sigma_R^* = \dfrac{S_R}{F_n}$

For an easier analysis of the results a relative scatter parameter is introduced for the customer severity the distributions: $\rho = \sigma_C/\mu_C$ and, ρ is representative of the shape of the "Stress" distribution. Using also the relative scatter q of the strength distribution introduced above, the ratio μ_Z/σ_Z can be written:

$$\frac{\mu_Z}{\sigma_Z} = \frac{m_R^* - \dfrac{1}{1+\alpha\rho}}{\sqrt{\left(qm_R{}^*\right)^2 \dfrac{N-1}{\chi^2_{\gamma(N-1)}} + \left(\dfrac{\rho}{1+\alpha\rho}\right)^2}}$$

the risk R is therefore a function of :

$$R = \text{Prob}\left(u < -\frac{\mu_Z}{\sigma_Z}\right) = f\left(\alpha, \rho, m_r^*, q, N, \gamma\right)$$

From the designer point of view, the only variable for the risk is the relative mean value m_R^* . It means that he should assume that the relative scatter of the component he will design is q. And he must design a component having the correct mean strength value.

When performing the experimental validation, the parameters α, ρ, q, N, and γ are known. The validation aims at the checking of the expected ratio between the mean value and the objective customer.

When performing the design calculation, the goal is the same, but it is necessary to introduce β, the number of standard deviation between F_D et m_R : $m_R = F_D + \beta s_R$ from which we can derive : $m_R^* = 1/(1-\beta q)$.

This expression can be introduced in the risk calculation. Then, β becomes the unknown, and one must identify the value that gives the expected risk. In the finite element analysis, the loading are given by F_n, and the acceptance criterion is the material fatigue criterion chosen at the mean value minus β standard deviations.

All the necessary statistical and probabilistic tools are now available in the software platform. The qualification of the reliability of the different cases studied in the project will be done on this basis.

5 WAITED RESULTS OF THE PROJECT

5.1 New tools for reliability analysis and new services

The project gives an answer to the new request that is rising around the topic of reliability in fatigue of structures and mechanical. Waited results are new products and methods answering the problems reliability for the engineer based on:

- **a modular software** made up of generic modules adaptable to the questions of each one
- **a know-how** adapted to industrial calculation methods and experimental means

The technical and scientific contents of the program will end in:

- the creation of a generic approach of fatigue design reliability of structures and mechanical components adaptable to the various industrial needs
- a software platform exploited by CETIM allowing the reception of the whole of the modules necessary and the extension to new modules resulting from the evolution of knowledge
- experimental practices adapted to the characterization of the fatigue parameters of the material/process couples and to its statistical contents with regard to the needs for modelling
- new experimental practices of validation of the provisional reliability of the industrial products
- methods of capitalization of the characterisation and the validation data

5.2 Industrial integration.

The project should make sure that the totality of the industrial constraints is well taken into account with respect to the applicability of the methods suggested and their appropriation by each industry. The project will have to take care of:

- the ways and means used in industry more than in research laboratories
- the regulation contexts if necessary
- the most adapted way for the dissemination of know-how at European scale.

5 CONCLUSION

This project has the ambition to introduce into the mechanical engineering industry the reliability approach for the fatigue design and validation of structures and mechanical components.

The objectives are: to build the necessary evolution to manage industrial projects by the technical risk's control, to create the engineering reliability culture, to develop adapted tools for industrial application.

The mastery of the design and validation reliability approach it is:

- the true driving force to the **structural optimisation**. With efficient methods and tools for provisional reliability analysis, the optimisation of structures and components make sense in term of weight saving and technico-economics performance. An optimisation based on the right and bare essentials will guarantee the cost control of the product when limiting inadapted safety margin.
- to be in a position to analyse in pragmatic way its product with regard to **the reliability performance waited by the customer**. Indeed the reliability approach asks for setting clearly the cycle of development cycle key points, the variety of in-service loading, the scatter in strength of the manufactured products, the definition of the acceptance criteria.
- to afford a strong element of decision taking for the acceptation of a design and a fabrication through the risk quantification and control.

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.

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