A MECHANICAL RELIABILITY APPROACH FOR HETEROGENEOUS WELDING DESIGN IN VIBRATORY ENVIRONMENT

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ABSTRACT

This work presents a mechanical reliability application for the fatigue design of a heterogeneous welded structure under dynamic loading.

A chain of numerical toolboxes is developed, based on 6 mains steps. Modal and structural computations using a structural stress damage criterion are realized. A probabilistic definition of the selected random variables is carried out and their influences are then taken into account by a numerical parametric study resulting from a design of experiments and leading to a sensibility analysis. An experimental validation of the results is also presented.

As an illustration, we applied this method in order to evaluate the reliability of an heterogeneous tantalum – Ta6V4 welded structure. The effect of the selected parameters on the damage criterion and therefore on the structure reliability is evaluated. This method leads to a fine knowledge of the reliability sensitivity linked to each parameter and is therefore a powerful tool for optimizing the design of a structure.

Moreover, a related application of the method is presented. The power spectral density (PSD) loadingn shows several critical frequency ranges with high excitation levels. The first modal frequency of the structure must be isolated from these frequency ranges. Depending on the first modal frequency value, the structure reliability can be affected. By using reliability methods, one can evaluate a distribution law of this parameter in order to maximize the structure reliability. This distribution law has to be checked on the structure.

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1. INTRODUCTION

The main objective of this study is to develop a whole chain of numerical toolboxes related to a simple method leading to the estimated reliability evaluation during the development of an heterogeneous tantalum – Ta6V4 welded structure under dynamic loading.

Figure 1 Numerical toolboxes

Firstly, the numerical toolboxes are presented. Numerical software were adapted in order to follow 6 steps:

- Modal identification of the structure ;
- Structural computations which need :
    - the choice of a damage criterion through a structural stress analysis ;
    - the definition of an equivalent displacement amplitude loading leading to the same damage

than generated with the random stationary ergodic dynamic loading.

- Probabilistic definition of the random variables (local geometry, material data, loading, resistance).
- Numerical parametric study to cover efficiently the range of interest of each variable and analysis of an optimized response surface in order to identify the distribution law of the local stress.
- Sensibility analysis of the structure reliability according to the random variables.
- Validation of the results using an experimental determination of the S-N diagram of the heterogeneous welded joint.

Figure 2 presents the structure:

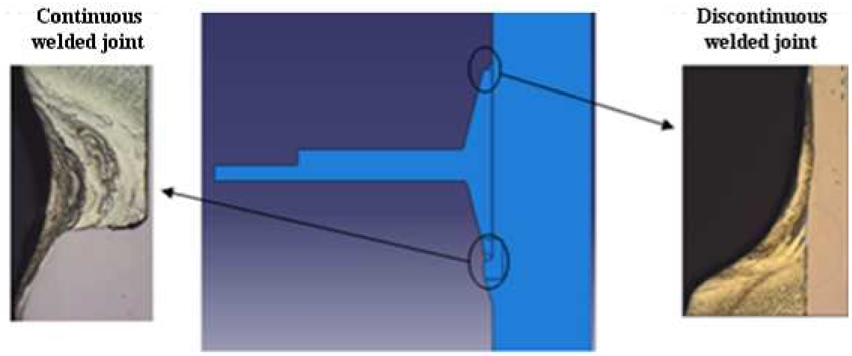

Figure 2 TA6V4 / Ta structure

Finally, the experimental methodology for the validation of the numerical results is presented. These tests are still in progress and preliminary results are presented in this paper.

2. NUMERICAL TOOLBOXES DEVELOPPMENT

2.1. MODAL IDENTIFICATION

In order to evaluate the damage induced to the welded joints during its life time, the dynamic response behavior to the source PSD is required. Therefore, the identification of the modal frequencies and modes is essential. A representative mass is implemented in the model. This mass is bounded to the extremity of the titanium part. Only the first mode, predominant on the dynamic behavior, is taken into account.

The first mode is identified (see figure 3) at a frequency f_0. The corresponding quality factor ($Q = 1/(2*\xi)$), experimentally determined, is around 30.

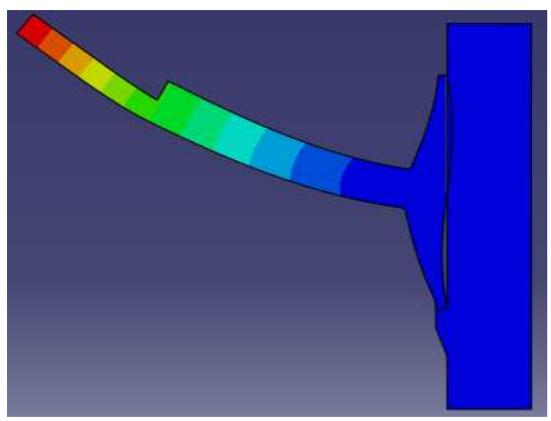

Figure 3 First mode of the structure

2.2. STRUCTURAL COMPUTATION

2.2.1 DISPLACEMENT BOUNDAY CONDITION DEFINITION

The mechanical structure is simulated as a one degree of freedom linear system (ddl: vertical displacement) characterized by mass, linear rigidity and damping coefficients.

The random stationary and ergodic vibratory signal is modeled by a PSD of several intervals of constants amplitudes.

The first modal frequency f_0 has been identified using numerical simulation. Its value is currently considered as deterministic. The quality factor Q is equivalent to a damping coefficient ξ less than 2%. Combined to a PSD of constant intervals, experimental feedback on its influence leads us to define Q also as a constant.

The irregularity factor of the dynamic response to the PSD is greater than 0.9. The structure response can therefore be considered as a narrowband signal. It is characterized by the RMS displacement (Z_{eff}) of the titanium part. This displacement is imposed as boundary conditions to the mass.

$$\mathbf{Z_{eff}^2 = \int_{\Omega_1}^{\Omega_2} G_s(\Omega) . H^2(\Omega) d\Omega}$$

With

- Ω=2pf : pulsation
- Gs(Ω) : PSD applied to the structure
- H(Ω) : transfer function (relative response)

2.2.2. DAMAGE CRITERION FOR THE WELDED JOINTS

The choice of the damage criterion is of first importance. The criterion is chosen among those already existing and which may be applied to welded joint (nominal stress [2][3], geometrical stress [2][3], structural stress [4][5][6], fracture mechanics [7]).

The significant and very local stress concentration, the size considerations and a supposed welded roots damage initiation lead us to choose a structural stress criterion.

A representative local model is chosen for the simulation. The influence of crack radius “r”, resulting from the gap between the titanium part and the tantalum cylinder, is numerically significant on the structural stress. It has therefore been noted that the structural stress increases when “r” decreases. However, as it is illustrated on figure 4, a critical value “r_c” has been determined experimentally (below this value, the lifetime is no more influenced). [7] [10]

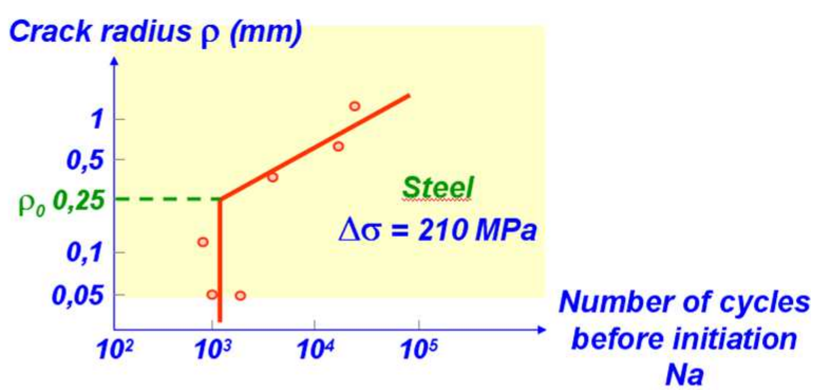

Figure 4 Crack radius influence on life time (from [7])

The order of magnitude of this “critical radius” is about three times the grain size of the material. This value is around 120µm for tantalum. As a result for this structure, a crack radius of a few microns (less than 10µm) is far below the critical radius.

The crack radius is therefore fixed to the median value observed on the welded joint micrographs. Moreover, “r” is considered as a fixed deterministic value for all this study.

As illustrated figure 5, the very thin welded zone needs mesh refinement. 2µm size around the crack radius (radius 8µm, zone n1) is required for results convergence. Other elements in the welded zone (n2) have a 10µm size. Near the welded zone (n3), a 50µm size is used and far away (n4), a coarser mesh of 500µm is enough. Computation times are acceptable using this mesh size.

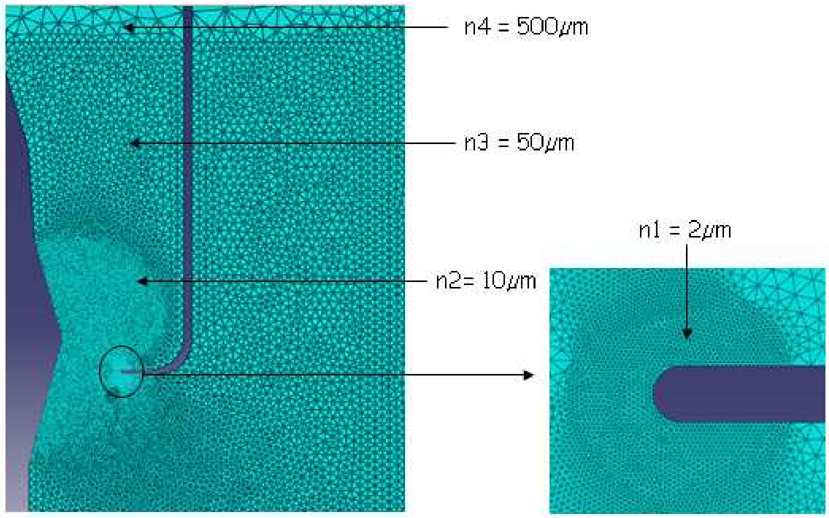

Figure 5 Mesh and submodeling of the welded zone

The structural stress criterion is the maximal principal stress at the crack tip. In our case, it is perpendicular to the welded joint.

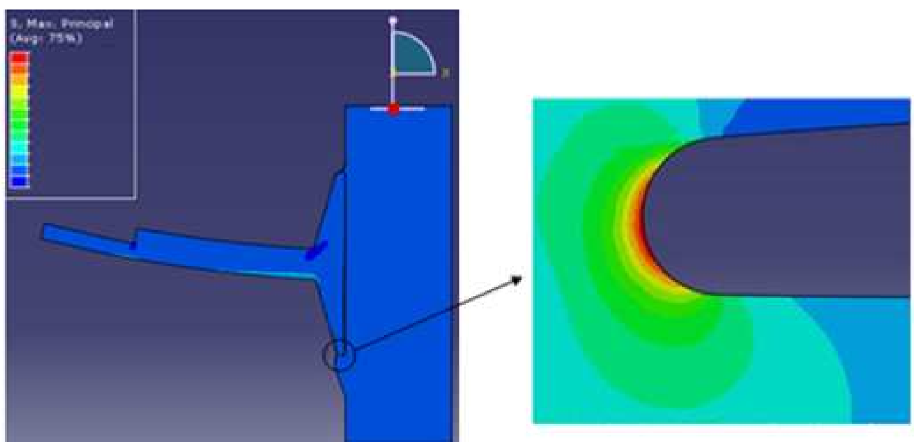

Figure 6: Continuous welded joint

2.3. IDENTIFICATION OF THE RANDOM VARIABLES

The most important random variables are chosen and their respective distributions laws are built. The most disadvantageous choice is made when information is lacked in order to define a reliable distribution law.

The numerical model of the welded zone is based on structural micrography (as proposed figure 7) for both continuous and discontinuous welded joints. Evaluation of the distribution laws of the chosen geometrical variables - α angle or welded depth Hl – is made using these micrographs.

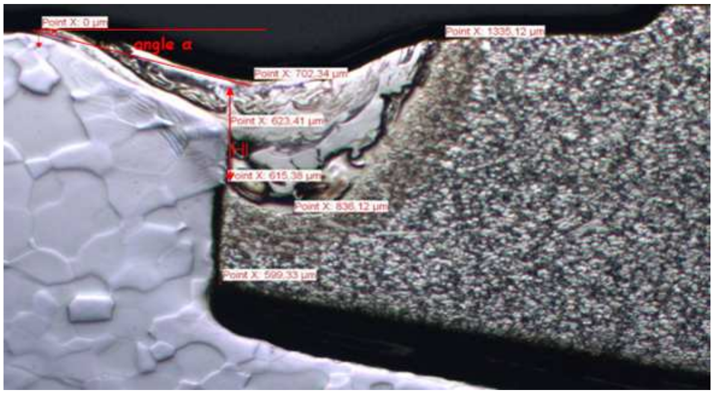

Figure 7 Continuous welded joint micrograph

Young modulus of the welded zone "E $_{welded}$" is also identified as a random variable (non geometrical).

A variation of the first modal frequency f_0 is taken into account later in this article. Indeed, the influence of f_0 on the value of Z_{eff} is affected by the discontinuous definition of the PSD. As a consequence, this is not convenient for a method of a continuous surface response.

Consequently, three random variables have been selected for this study: E $_{welded}$, alpha and Hl. A previous work [11] and the micrographs are used to identify their distributions laws. As explained previously, the crack radius has been dismissed.

The distributions laws are presented below:

Alpha, E_{welded}: normal distribution:

	α (°)	E_{welded} (GPa)
Mean value μ	15	92
Standard deviation σ	1,5	9,3

Hl: Weibull distribution:

Shape parameter β	13,85
Scale parameter η	382
Lower bound δ	0

As illustrated in figure 8, the Weibul law is non symmetric and smoothed on the small values of welded depth. This means that the small values ratio is more significant than the high values ratio.

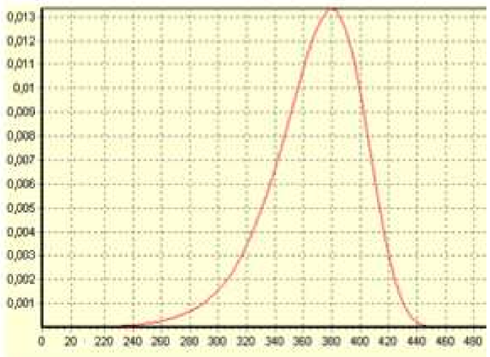

Figure 8 Hl: Weibull distribution

2.4. DEFINITION OF THE NUMERICAL DESIGN OF EXPERIMENTS

Two different kinds of numerical design of experiments are used: "quasi–random" experiment or central composite experiment as shown in figure 9.

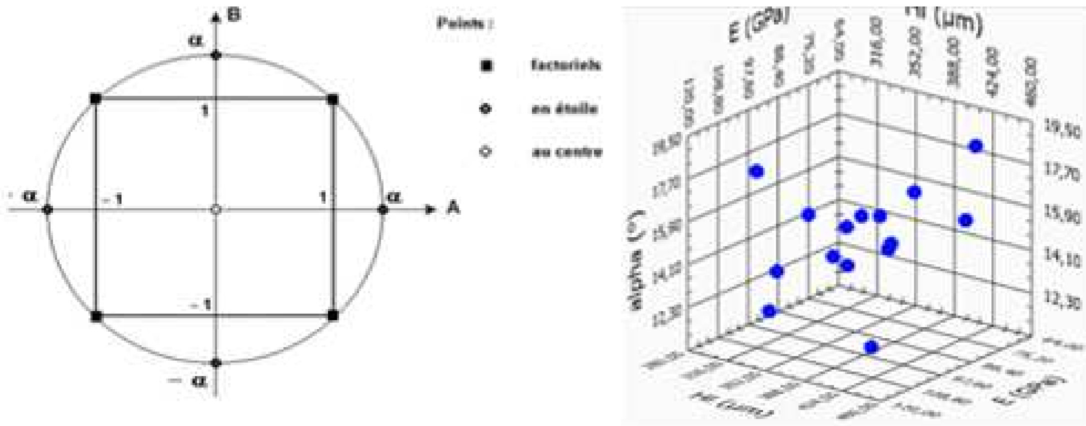

Figure 9 Two variables central composite (left) and three variables quasi random (right) experiments

The “quasi-random” experiment uses both methods of LHS (Latin Hypercube Sampling) algorithm and multiple regression. The coordinates of its points are given by a random sampling adjusted by the variables distributions laws. The design of experiment is therefore richer where the variables distribution laws are higher. As the failure probability expected is very low, each variable has to reach values far from the medians (to several standard-deviations from the medians). Some points are thus fixed to the borders of the variables distribution laws (three to five standard-deviations) in order to provide an interpolation domain including the design point.

Advantages of the “semi-random” experiment:

- Easy to build;
- Very realistic location of the points while insuring an interpolation domain including the design point.

If the accuracy of the first surface response obtained is inadequate, a central composite experiment [13], centered on the previous approximated design point, is realized. Central composite experiment is made of three parts: a factorial experiment, several axial points and one central point.

Advantages of the central composite experiments:

- Possibility of working step by step: the factorial experiment can be analyzed before evaluating other points. If the resulting surface response is accurate enough for our study, there is no need to evaluate the other points.
- Possibility to evaluate numerous values for each variable: for instance, for a design of experiments composed of three variables and fifteen points, five different values for each variable can be tested.

2.5. DESIGN OF EXPERIMENTS ANALISYS AND RESPONSE SURFACE CREATION

Using multiple regression method and based on the results at the n points of the design of experiments, a response surface of the damage criterion is evaluated. This response surface has a polynomial function shape. One can therefore estimate the damage criterion in the entire interpolation domain.

In order to validate the response surface obtained, several tests are applied:

- The Fisher-Snedecor test checks if the whole group of studied variables has a real impact on the damage criterion;

- The Student test identifies which variable have a real influence on the damage criterion and which are their adequate degrees in the polynomial response surface. A square surface response seems well adapted to our project. Another methodology consisting in saturating the polynomial function with as many factors and degrees possible has been tested. Compared to the previous one using the Student test and an optimized response surface, it has been demonstrated less effective.

- Validation tests of the surface response by evaluating new points in the interpolation domain to check the quality of the model (see figure 10).

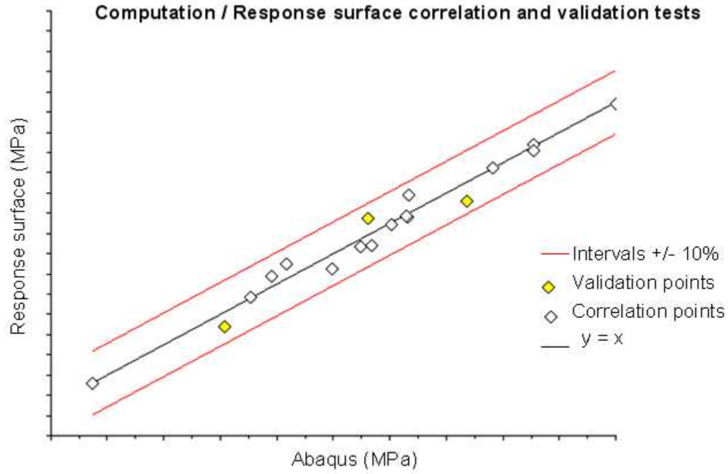

Figure 10 Validation tests for the response surface

2.6. RELIABILITY ANALYSIS

2.6.1. RESISTANCE DISTRIBUTION LAW IDENTIFICATION

The “Stress - Strength” method is applied to evaluate the reliability of the structure under fatigue solicitations for a fixed number N of constant sinusoidal cycles.

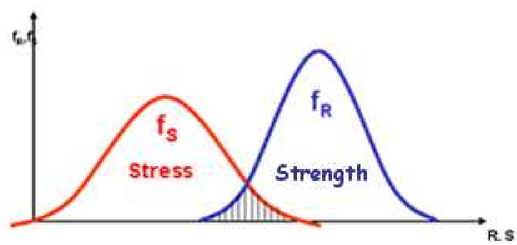

Figure 11 Stress – Strength method

The Stress distribution (S) law is identified by the surface response resulting from the design of experiments corrected by its residual standard deviation (which represents the model inaccuracy). It gives the probability density of the maximal principal stress at the critical zone associated to the relative effective displacement Z_{eff}.

The Strength distribution (R) law under fatigue loading of the heterogeneous welded joint should also represent the maximal principal stress at the critical zone and be associated to the PSD and its application duration T. An S-N diagram is therefore required.

Some results of previous fatigue experiments on the heterogeneous welded joint under constant alternate sinusoidal signal have been exploited. Using simulations, they have been formulated in critical local stress. They enable us to build the best fit for a Wöhler curve. One can fit the coefficients of the Basquin’s model associated. This optimization leads to the following first approximation of a Basquin’s model in local stress:

$$N*\sigma_R^{\,b} = C \text{ with } b=6.9$$

Future experiments will give us a more accurate value of the b coefficient needed for the “construction” of the Strength distribution.

To compare the response surface (Stress) to the Basquin’s model (Strength), an equivalent law between the PSD of duration T and the number N_{equi} of sinusoidal constant cycles has to be applied. According to [1] and [14], when dealing with a narrowband signal, the damage equivalent alternate sinusoidal signal to a PSD of duration T (random stationary and ergodic vibration) and of effective displacement Z_{eff} is given by the equations below :

$$N_{equi} \approx r.n_p^+.T.\Gamma\left(1+\frac{b}{2}\right)$$
$$Z_{a\ equi} = \sqrt{2}\,Z_{eff}$$

With:

- r : irregularity factor (r>0,7)
- n^+_p : mean frequency of the maxima (Hz)
- T: DSP duration.
- b : b coefficient of the Basquin's model
- Γ : *Gamma function* $\Gamma(1+b/2)=(b/2)!$

N_{equi} cycles of constant amplitudes $Z_{a\ equi}$ leads theoretically to the same damage on the heterogeneous welded joint than the PSD of duration T. N_{equi} is thus the cycle number to apply to the Basquin's model to read the Strength value σ_R for the "Stress – Strength" method. As required when using a Basquin's model, strength follows a log-normal distribution. Its variation coefficient, according to the experimental feedback, is estimated to 10%.

Next, we will see how the Basquin's model can be corrected using the reliability experimental results on the welded joint.

2.6.2. RELIABILITY ESTIMATION OF THE STRUCTURE

There are several methods to model the limit state function G = Strength – Stress [15]:

- Approximation methods (cf. figure 12) : FORM (First Order Reliability Method) or SORM (Second Order Reliability Method) ;
- Simulation methods: Monte Carlo, Subset, Importance…

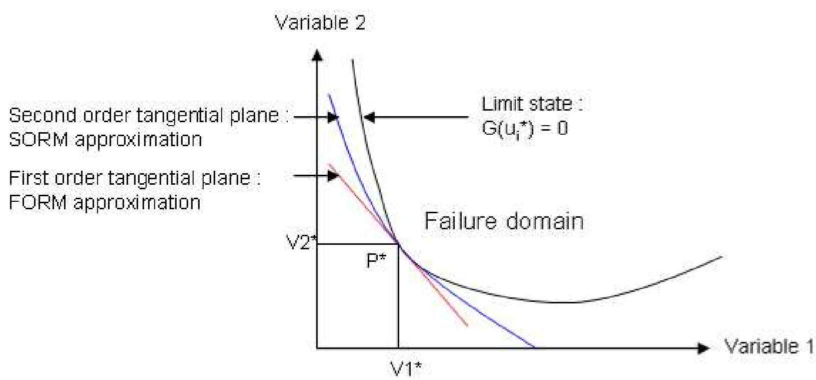

Figure 12 FORM and SORM methods

Phimecasoft software realizes this step of the study [16].

As a second order polynomial function is used here, the SORM approximation method is especially adapted.

The whole method applied to the structure leads to a failure probability of magnitude 10^{-7} for the discontinuous welded joint and 10^{-9} for the continuous welded joint. These values are obtained with an approximate Strength distribution. They are presented essentially to illustrate the final results of the method.

The reliability analysis leads also to a ranking of the influences of the variables:

- α influence is none significant;
- Hl and E are significant.

The crack radius had been dismissed by the bibliography which shows that below a critical value (close to three grain size) this radius does not impact life time.

2.6.3. SENSIBILITY ANALISIS TO THE MODAL FREQUENCY F_0

Up to this point, the first modal frequency f_0 is supposed to be deterministic. Three reasons justify this choice:

- The lack of information to build the distribution law of f0 (as we develop the method).
- The response surface built with f_0 as a variable is very inaccurate. Indeed, the discontinuous definition of the PSD results in an important discontinuity of the effective displacement Z_{eff}. F_0 influence on Z_{eff} and σ_{max} is illustrated on figure 13 :

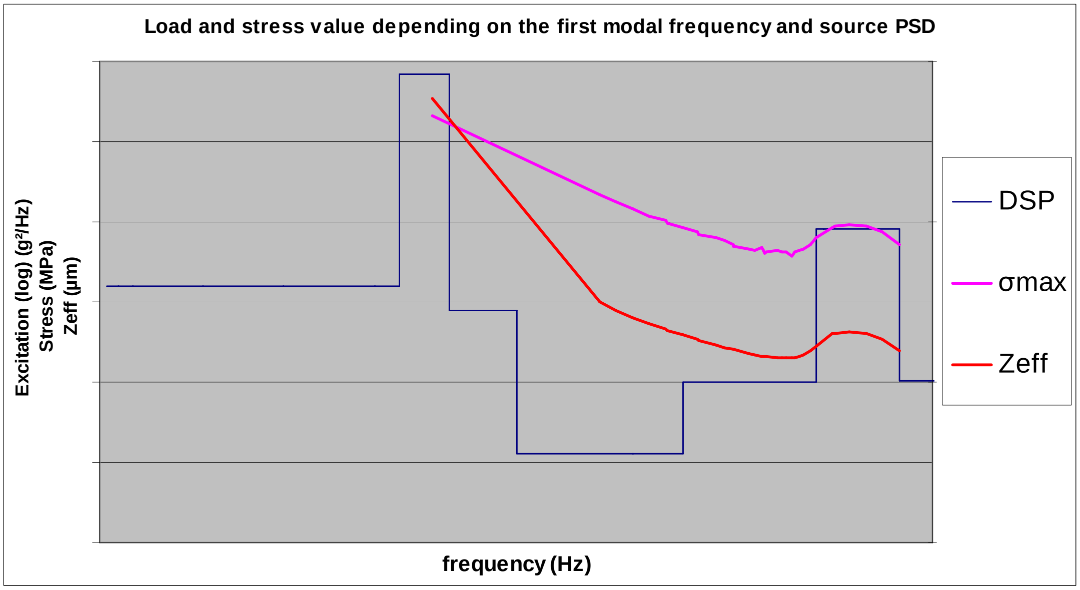

Figure 13 Source PSD and f_0 influence on stress and effective displacement

- As a consequence, f_0 has a huge influence and hides the effect of any other variables:

Variables	Importance factors
E	0.7%
Hl	0.45%
F_0	**86.7%**
Strength	12.2%
Residual standard deviation	0.05%

Figure 14 Importance factors for the variables E, Hl and f_0

f_0 has then a very significant influence and its distribution law is still unknown. The new goal is therefore to identify a reasonable distribution law of f_0 restricting its impact on the structure reliability.

An estimation of the failure probability is then performed considering several values of f0 at the center of each PSD interval. All the other variables are here fixed at their nominal values. Results are presented on figure 15:

Interval	1	2	2-3	3	4	5	6
f_0 (Hz)	$0{,}7 * f_0$	$0{,}9 * f_0$	$0{,}9 * f_0$	f_0	$1{,}1 * f_0$	$1{,}2 * f_0$	$1{,}3 * f_0$
Z_{eff} (µm)	38	22	20	16	15	21	11
σ_{max} (MPa)	$2{,}5 * \sigma_{max}$	$1{,}46 * \sigma_{max}$	$1{,}29 * \sigma_{max}$	σ_{max}	$0{,}99 * \sigma_{max}$	$1{,}33 * \sigma_{max}$	$0{,}7 * \sigma_{max}$
Pf	≈ 1	10^{-1}	$6*10^{-3}$	$1{,}4*10^{-7}$	$9*10^{-8}$	$1{,}5*10^{-2}$	$1{,}6*10^{-18}$

Figure 15 Failure probabilities depending on the value of f_0

Classically, the next step is to assume that the failure probability can be estimated by the multiplication of the failure probability, considering f_0 constant in one of the PSD interval, and of the probability for f_0 to belong to such interval:

$$P_f \text{ associated with an interval} = P_f(\sigma_{max}/f_0) * Prob(f_0 \in \text{ interval})$$

Finally, we seek the distribution law of f_0 (supposed as a normal distribution) while minimizing the failure probability (less than 10^{-7}) whatever f_0 value.

The smallest value of standard deviation resulting from this criterion leads to a tolerable standard deviation of 2.5% on the first modal frequency.

This method allows us to evaluate an acceptable distribution of f_0 in order to limit its impact on the structure reliability. This distribution law can therefore be used as a conception objective to maintain under control the structure dynamics characteristics.

3. EXPERIMENTAL DEMONSTRATION OF THE NUMERICAL RESULTS

The goals of the mechanical tests currently in progress are:

- To validate the critical zone and failure location;
- To demonstrate the reliability law of the welded joint
- To demonstrate the theoretical equivalent law between DSP solicitation and constant sinusoidal solicitation;
- To improve the Basquin's model identification (b coefficient) of the welded joint.

3.1. TESTS ON THE STRUCUTRE AND INSTRUMENTATION

Tests are performed using an electrodynamics shaker Ling395 on an adequate test assembly (figure 16):

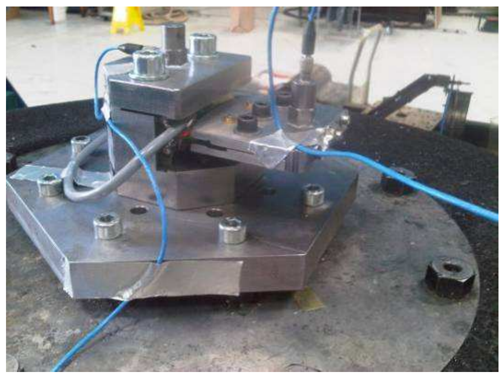

Figure 16 Assembly and shaker

- The dynamic response of the structure is measured by a triaxial accelerometer fixed at the center of the mass bound to the structure.
  - o Complementary measurements : strain measurements near the continuous welded joint (two captors J1 and J2 perpendiculars to the welded joint) and discontinuous (one captor J3 perpendicular to the welded joint)
  - o None contact measurements of the vertical displacement using a laser vibrometer.

- The test is considered completed and fracture is checked when the evolution of the dynamic response of the structure exceeds a fixed threshold. As one can see figure 17.

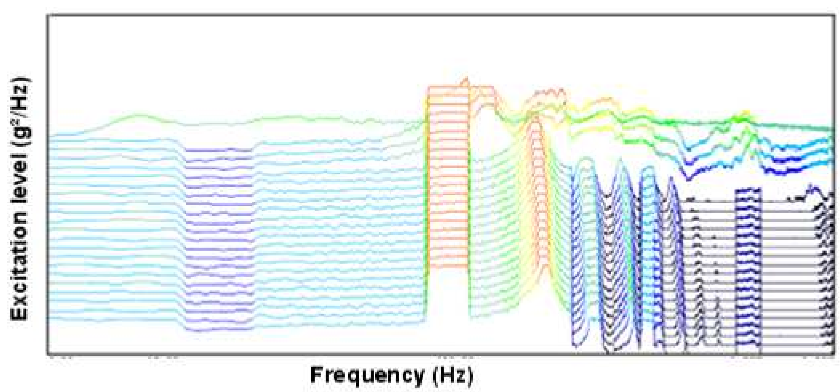

Figure 17 Fracture detection on the dynamic response

3.2. TESTS METHODOLOGY

- Dynamics characteristics of the structure are identified by the mean of a sinusoidal signal and a logarithmic sweep (1oct/min) loading.
- The two hours duration PSD which leads to a unitary median damage is established by an increasing damage test (LOCATI test).
- S-N curve is determined both by means of PSD (9 tests) and constant amplitude sinus loading (4 tests) using Dwell tests.

3.3. PRELIMINARY RESULTS

- The first mode of the assembly has a very weak damping which is favorable to the tests reproduction. Scattering of the first modal frequency obtained during the tests is close to 3%. This value is close to the coefficient of variation recommended for the reliability optimization.

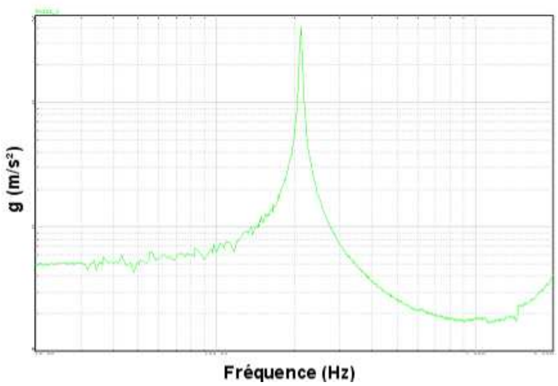

Figure 18 vibratory signature of the structure

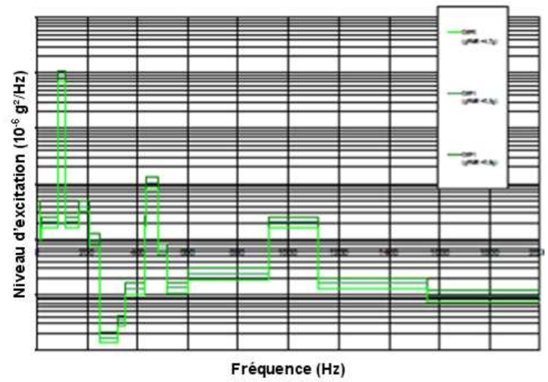

Figure 19 PSD applied

- The rupture initiation in the discontinuous welded joint is demonstrated. The detection method used here enables us to stop the test when the crack initiation appears in the discontinuous welded joint.

- The S-N curve is still in progress. The first tests results allow to establish a Basquin's model of slope b close to 6 and therefore validate the previous approximation (b = 6.9).

- Validation of the coherency between the PSD and the effective relative displacement is not yet obtained by the experimental results. We currently propose to explain this by the fact that the modal frequency value f_0 is at the edge of two quite different loading levels of the PSD. This leads to calculate quite different values of the effective displacement $Z_{eff.}$ However, it is probable that this discontinuity is smoothed during the tests. Next tests will be carried out with PSD intervals amplitudes similar to the neighborhood of f_0, avoiding then such discontinuity.

CONCLUSION:

- A chain of numerical toolboxes has been created by building links between several software and by the development of a specific methodology. It leads to the assessment of the reliability of a welded structure under stationary dynamic loading.

- This numerical method, combining two different designs of experiments, one deterministic and another stochastic, takes into account both the random characteristics of the loading and the welded joint. Moreover, compared to a full stochastic approach, the time required for the evaluation of the response surface has been optimized.

- The sensibility analysis to the "interesting variables" of this reliability evaluation associated to a SORM approximation method leads to an upstream definition of the intervals of tolerances of the dynamic characteristics - and especially the first modal frequency - of the structure. This definition limits the impact on the reliability.

- The experimental validation of the numerical method will complete later this article thanks to both tests under dynamic random solicitation (PSD) and fatigue tests under sinusoidal signal (constant frequency and amplitude). It will enable us to calibrate the Strength distribution of the heterogeneous welded joint. Moreover, the tests should also validate the theoretical equivalent damage rule between life time under PSD and number of cycles of deterministic sinusoidal signal. This equivalent rule, applied during a development phase, could lead to an important time reduction for the reliability and safety demonstration. However, it requires a fine knowledge of the b coefficient of the Basquin's law.

- Once fully achieved, this reliability assessment method under dynamic loading can be applied to other failure modes and damage criterion. It will however require the same special care to the coupling between tests and computations to determine the strength distribution resulting of both material and process.

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