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FATIGUE ANALYSIS OF STRUCTURES DURING RANDOM LOADINGS

We have developed and described a special approach for long life fatigue analysis of welded structures under random multi-axial loadings, which has a real physical meaning and which is very easy to perform. The principal idea is to find an equivalent simple loading suitable to represent the real random loading in terms of damage produced at the level of the material then at the level of the structure.

Keywords: fatigue analysis, structure, random loading, software, welded structures.

Abstract. We have developed and a special approach for long life fatigue analysis of welded structures under random multi-axial loadings. During classical analysis, a linear or non-linear finite element simulation is usually performed, and then eventually with some special methods to extract and to count the cycles from the random stress path (very often, the Rainflow method), it is needed to cumulate "damage" based on some S-N diagrams and the linear Miner-Palmgreen rule or some more elaborated non linear rules. The "damage" factor (scalar or tensor) is still the object of many researches; it is impossible to measure it during the whole loading path, even if, before failure; some slight changes on the elastic properties may be experimentally detected. Moreover, the representations of the loading and the counting methods are purely based on mathematical aspects and ignore the particular mechanical behavior of the present materials in the structure.

The objective of our paper is at first to describe an approach which has a real physical meaning and which is very easy to perform. The principal idea is to find an equivalent simple loading suitable to represent the real random loading in terms of damage produced at the level of the material then at the level of the structure.

We introduce a global representation of any loading at the scale of the material to give the equivalence rule between any two loadings at the scale of the material and to allow to represent any random loading by an equivalent periodic loading. We chose as a "measure" of any one-parameter random loading, the cumulated plastic strain (or equivalently the dissipated energy) at a new very local level (similarly to what it is done during a seismic analysis). Two loadings are equivalent if they induce the same cumulated plastic strain (or the same dissipated energy).

The other objectives refer to that during fatigue analysis:

1) we have to take into account the in certainties on geometry, material properties, loadings;

2) we have no knowledge of the real initial state;

3) and also, we can not control the errors during numerical simulations or measurements.

To cross over these difficulties a new framework for fatigue analysis and reliability of structures has been built which allows the analysis to be reduced to

the analysis on a 2-D window with a Characterized radial cyclic loading. It is given one description for the smooth specimen and any general structure with any loading conditions; simplified analysis of inelastic structures and simple rules for damage and accumulation are taken but the results are coupled with results from returns on real structures.

All these procedures and framework were introduced in a Software, FATPRO, that is developed and distributed by CADLM. http://www.cadlm.fr/page.php?page=coit_log_fatpro&lang=anglais

Review on the inelastic analysis of structures. We are concerned by a general structure which is subjected to a general complex cyclic static or dynamical loading. It is well known that even if there is no collapse or ratcheting or excessive deformation, after a while, there will be shakedown and then failure of the structure by fatigue. We have proposed a very simple and practical framework for this analysis. All details may be found in the book [1].

Loadings on the structure. The structure has the volume Ω with the surface $\partial\Omega$. It is subjected to the following loading:

– on a part $\partial_{Uj}\Omega$ de $\partial\Omega$: given displacements $U_j^d(t)$;

– on the complementary part $\partial_{Fi}\Omega$ de $\partial\Omega$: given surface loads $F_i^d(t)$;

– in the volume Ω: specific load $X^d(t)$;

– in the volume Ω: initial strains $\boldsymbol{E}^I(t)$.

The full data $U^d(\tau)$, $F^d(\tau)$, $X^d(\tau)$, $\boldsymbol{E}^I(\tau)$ for any $\tau \in [0, t]$ characterizes the loading path on the structure.

Purely elastic response. At first the structure is assumed made of linear elastic materials. At any time t, the elastic response is given by :

– the elastic displacement $U^{el}(t)$;

– the associated strains $\boldsymbol{E}^{el}(t)$;

– the elastic stresses $\Sigma^{el}(t)$ by using any tool ***ELAS*** which has the arguments: ***ELAS*** $\{\Omega, \partial_{Fi}\Omega, \partial_{Uj}\Omega, X^d, F_i^d, U_j^d, \boldsymbol{E}^I, \boldsymbol{M}\}$, where $\boldsymbol{M}$ is the elastic coefficient matrix ($\boldsymbol{M}^{-1} = \boldsymbol{L}$)

$$\Sigma^{el}(t) = \boldsymbol{L}(\boldsymbol{E}^{el}(t) - \boldsymbol{E}^I(t)).$$

Real response. There will be in the structure the fields: $U(t)$,$\boldsymbol{E}(t)$ Kinematically Admissible with $U_j^d(t)$, on $\partial_{Uj}\Omega$

$$\boldsymbol{E}(t) = 1/2(\nabla U(t) + \nabla^T U(t)).$$

$\Sigma(t)$, Statically Admissible with $X^d(t)$ *in* Ω *and* $F_j^d(t)$, *on* $\partial_{Fi}\Omega$

$$\Sigma(t) = \boldsymbol{L}(\boldsymbol{E}(t) - \boldsymbol{E}^I(t) - \boldsymbol{E}^p(t)).$$

These fields may be split into one elastic part (previously analyzed) and one inelastic part:

$$U(t) = U^{el}(t) + U^{ine}(t);$$

$$\boldsymbol{E}(t) = \boldsymbol{E}^{el}(t) + \boldsymbol{E}^{ine}(t);$$

$$\Sigma(t) = \Sigma^{el}(t) + \boldsymbol{R}(t),$$

where $U^{ine}(t)$, $\boldsymbol{E}^{ine}(t) = \boldsymbol{M}\,\boldsymbol{R}(t) + \boldsymbol{E}^p(t)$ K.A. with 0 sur $\partial_{Uj}\Omega$; $\boldsymbol{R}(t)$ is S.A. with 0 in Ω and 0 on $\partial_{Fi}\Omega$**.**

These inelastic fields may be obtained, when the plastic strain filed is known, with: $\boldsymbol{ELAS}\{\,\Omega\,,\partial_{\,Fi}\Omega\,,\partial_{\,Uj}\Omega\,,0,0,0,\boldsymbol{E}^p,\boldsymbol{M}\}$, which means that:

$$\boldsymbol{R} \equiv Z_0 \boldsymbol{E}^p,$$

where Z is an integral operator on the plastic strain field.

Particular case of the cinematic hardening material. This material associated to the Mises criterion is classically defined by:

$$f(\Sigma\,,\boldsymbol{y}) = f(\boldsymbol{S}\text{-}\boldsymbol{y}) = 1/2\,(\boldsymbol{S}\text{-}\boldsymbol{y})^T(\boldsymbol{S}\text{-}\boldsymbol{y}) - \sigma_0^{\,2},$$

where $\boldsymbol{S}$ is the deviatory part of the stress tensor and which defines in the stresses space the moving convex elastic surface $C(y) = C_0 + \boldsymbol{y}$.

The internal parameters are here the plastic strain tensor; the transformed internal parameters $\boldsymbol{y}$ are linked to $\boldsymbol{E}^p$ by: $\boldsymbol{y} = \boldsymbol{C}\,\boldsymbol{E}^p \Longleftrightarrow \boldsymbol{E}^p = \boldsymbol{C}^{-1}\,\boldsymbol{y}$; $\boldsymbol{C}$, is the work-hardening matrix.

The normality flow rule is classically written symbolically: $\boldsymbol{E}^{\cdot p}(t) \in \partial\Psi_{C(y)}\,(\Sigma\,(t))$ i.e. external normal cone to $C(y)$ at Σ.

By using $\Sigma \equiv \Sigma^{\,el} + \boldsymbol{R}$ the yield criterion may be rewritten:

$$f(\Sigma^{\,el} + \boldsymbol{R} - \boldsymbol{C}\,\boldsymbol{E}^p)$$

and then as

$$f(\Sigma^{\,el} - \boldsymbol{Y}),$$

where $\boldsymbol{Y} = \boldsymbol{C}\,\boldsymbol{E}^p - \boldsymbol{R}$ is the structural transformed parameters field.

It is obtained with the procedure $\boldsymbol{ELAS}$ $(\Omega, \partial_{\,Fi}\Omega, \partial_{\,Uj}\Omega, 0, 0, 0, \boldsymbol{E}^p, \boldsymbol{M})$, which means $U^{ine}(t)$, $\boldsymbol{E}^{ine}(t)$, $\boldsymbol{R}$ and then $\boldsymbol{Y}$.

The main point is that: since at any time $\Sigma^{\,el}$ is known independently of the previous load history, the $\boldsymbol{Y}$ is a locally known position

$$C(\Sigma^{el}) = C_0 + \Sigma^{el}\ \ !!$$

Very often, it is possible to guess or to obtain exactly, the actual position of the structural transformed parameters field $\boldsymbol{Y}$, but it is, then, necessary to come back to the classical fields in order to characterize the eventual damage of the structure.

So, if the field $\boldsymbol{Y}$ is assumed known, the same operator with the new arguments $\boldsymbol{ELAS}$ $(\Omega\,, \partial_{Fi}\Omega\,, \partial_{Uj}\Omega\,, 0, 0, 0, \boldsymbol{Y}/\boldsymbol{C}, \boldsymbol{M}^{'})$ gives $\boldsymbol{R}$ and then $\boldsymbol{E}^p$. $\boldsymbol{M}^{'}$ is the modified elastic matrix ($\boldsymbol{L}^{'} = \boldsymbol{M}^{'\,-1}$) given by:

$$\boldsymbol{M}^{'} = (\boldsymbol{M} + \boldsymbol{C}^{-1} dev).$$

The one to one relation in the structure between the 2 fields $\boldsymbol{E}^p$, $\boldsymbol{Y}$ is then elementary to expressed.

During monotonic radial loading, an ultimate state is reached and is constructed exactly.

During cyclic radial loading, bounds are constructed with elementary rules.

Even during contacts loadings such as successive rolling or impacts (which are not classical loadings) or dynamical loadings such as seismic loadings, it is possible to propose special simple rules.

Review on the intelligent optimal design of materials and structures [2].

Automatic learning expert systems. The engineers have to face very important problems in the design, the test, the survey and the maintenance of their structures.

These problems did not yet get full answer even from the best people in the world. Usually in these problems (such as no satisfactory constitutive modeling of materials, no real control of the accuracy of the numerical simulations, no real definition of the initial state and/or the effective loading of the structure), there is no solution and the experts do not understand the problem in its whole. Moreover, the available data may be not statistically representative (i.e. are in limited number), and may be fuzzy, qualitative and/or missing in part. Other methods need to be used!

An automatic learning expert systems generator is able to automatically extract the rules from the raw examples base given by the expert. The experts know they do not know the full solution but they are able to build an examples base, for which the solution is known experimentally or numerically. Their main problem is to provide a good description of such an examples base. (By analogy, we can say that the data base is the program, the automatic learning tool is the compiler and the execution gives the knowledge).

Basically such a automatic learning system includes five main functions:

PREPARE: to transform the example files from user format (ASCII, Excel, ...) into the own format of the system and to handle the discretization of the descriptors and the splitting of the initial data base into a training set and a test set;

LEARN: to automatically extract a rules base from the training set according to the quality of available information (noise, sparseness of the training set,..) using Statistical, Symbolic, Numerical, Fuzzy logic, Neural Network or Genetic Algorithm learning;

TEST: to experimentally evaluate the quality of the extracted rule on the test set;

INCLEAR: to allow the expert to visualize IN CLEAR the extracted rules with the initial user format and to say what descriptors are the pertinent descriptors which are kept;

CONCLUDE: from the description of a new case, to deliver a conclusion based on the extracted rules.

In all problems, it is necessary to consider one conclusion which may be a class or any continuous real number. Moreover, often, several conclusions may be considered together. The rules have to be automatically generated for each one of them.

Then an optional but fundamental sixth function, OPTIMIZE, based on genetic algorithms and other special optimization techniques, may be used to solve the inverse problem i.e. when some conclusions and some descriptors have to belong to some given sets (or constraints), what are the possible solutions and in some particular cases what is the best solution if an objective function is given (cost, weight)?

Several automatic learning systems are now available. For example, at the Ecole Polytechnique in France, the LES program has been developed based on symbolic learning and numerical learning (by M. Sebag and M. Terrien) but also the Wards systems Group at Frederick, MD in USA, proposes the Neuroshell program witch is based on neural networks. These two programs are coupled with optimization add ones.

General principle of the approach. We have defined a new approach where it is needed:

1) To build a DATABASE of examples i.e. to obtain some experimental, real or simulated results where the EXPERTS indicate all variables or descriptors this may take a part. This is, at first, done with some PRIMITIVE descriptors $\boldsymbol{x}$,

which are usually in a limited number and which are often in a different number and type for each example. Then, the data are transformed with the introduction of some INTELLIGENT descriptors ***XX***, with the actual whole knowledge thanks to (but often insufficient) beautiful theories and models. These descriptors may be number, Boolean, strings, names of files which give access to data bases, or treatments of curves, signals and images. But for all examples, their number and their type are always the same, which is the only one way to allow the fusion of data. The results or conclusions may be classes (good, not good, ...) or numbers.

Usually, it is hoped to be possible to get ~50 to 500 examples in the data base with 10 to 1000 descriptors, 1 to 20 conclusions for each case. This is the most important (and difficult) task;

2) To generate the RULES with any Automatic Learning Tool. Each conclusion is explained as function or set of rules of some among the input intelligent descriptors with a known reliability or accuracy. If this reliability is too low, that means that there is not enough data or we have bad or missing intelligent descriptors;

3) To optimize at two levels (Inverse Problems).

Considering the intelligent descriptors as independent; it is possible to get the OPTIMAL SOLUTION satisfying the special required properties and allowing the DISCOVERY OF NEW MECHANISMS.

Considering the intelligent descriptors linked to primitive descriptors for a special family; it is possible to obtain the optimal solution that is technologically possible.

So, not only a Practical Optimal Solution is obtained but also the Experts may learn the missing parts, may build models or theories based only on the retained intelligent descriptors and guided by the shapes of the rules or relationships.

General description of mechanical problems. Several tools were built to describe most of the mechanical problems. It is necessary to describe them in an "intelligent" way.

Material descriptors. We use classical terms according the problem elastic coefficients, plastic properties, rupture and fatigue properties. All these descriptors are obtained on smooth specimen.

Field descriptors. At any given time, any scalar field M varying between M_{min} and M_{max} may be characterized with:

1) the interval $[M_{min}, M_{max}]$ is divided in n equal segments;

2) the relative surfaces in the window for which the scalar M is included in the interval n, (S_n/S_0), where S_0 is the surface of the domain.

Very often, we assume that the stress field at a given time is represented by I1, its first invariant, J2, the second invariant of its deviatory part and the norm of the gradient of this J2 (the problem being the fatigue life).

It is also necessary to describe the evolution of the stress field with the time. Hablot [3] introduced:

– $\phi_1 = \mathrm{Sup}_t\ [M / \mathrm{Sup}_\Omega\ (M)]$ envelop during the time of the relative M (included between 0 and 1);

– $\phi_2 = \mathrm{Sup}_t\ [M]$ envelop along the time of the absolute value;

– $\phi_3 = r_r\ \mathrm{Sup}_t\ [\|\ \mathrm{grad}\ \{(M) / \mathrm{Sup}_\Omega\ (M)\}\ \|]$ envelop of the norm of the gradient of the relative equivalent stress. This field shows the location of the maxima of the gradient during the evolution;

– $\phi_4 = r_r \, Sup_t$ [|| grad (M) ||]envelop of the norms of the absolute gradient, which expresses the most important gradients reached during the evolution;

– r_r is a characteristic dimension.

Many other quantities were also defined to represent curves, signals and pictures.

In order to follow our "intelligent" approach for the fatigue analysis, we need o create a data base of examples/problems. Each case/problem is at first defined by its primitive description. There is no way, with such a description, to use the results obtained from one case into another case/problem. The intelligent description has then to be performed.

Since, we can not rely to the numerical (or experimental) results for the classical LOCAL dimensioning criteria, we proposed to perform only the cheapest elastic analysis or our simplified analysis of inelastic structures and to use only the simplest rules for damage criteria and cumulating of damage for materials but we shall couple them with the results from returns on real structures.

Fundamental data on materials. On a smooth tensile specimen, it is easy to perform the following characterizations:

At first, the cyclic curves at ~± 1% of deformation are obtained (this is the best choice since the first tensile curve is a function of the initial state of the material, but it implies that the material is cyclically stable) eventually for different temperatures. Usually, these curves are represented by:

$$\varepsilon = \varepsilon_e + \varepsilon_p = \sigma / E + [\, \sigma / K' \,]^{1/n'},$$

where K' and n' are constant.

Then, the Woehler curves are constructed during cyclic uniaxial loading, associated to various mean radial stresses and probabilities of failure:

$$\sigma_{\max} = \sigma_a + \sigma_0 \,,$$

is the maximum or peak stress, where σ_a is the stress amplitude and σ_0 is the mean stress.

As proposed by the experts, they are represented by the stress-life equation:

$$\sigma_a = \sigma_f (2N_f)^b - S_d,$$

or, more practically, as in the Morrow's representation, by the strain-life equation:

$$\Delta \varepsilon / 2 = (\sigma_f' - \sigma_0)/E(2N_f)^b + \varepsilon_f' \, (2N_f)^c.$$

In this equation, S_d is the endurance limit during alternating cycles; $\Delta\varepsilon/2$ is the strain amplitude; $2N_f$ is the number of cycles to failure with the constitutive constants for the material; σ_f' is the fatigue strength coefficient; E is the Young modulus; ε_f' is the fatigue ductility coefficient; c is the fatigue ductility exponent; b is the fatigue strength exponent.

Then, the endurance diagram are constructed. A modified Goodman's diagram is usually employed for a given number of cycles, N, in the plane (σ_m, σ_a), a bounded domain is defined:

Rupture after N cycles if :	for
$\sigma_{max}-2\sigma_{m}\geq\sigma_{y}$	$-\sigma_{y}\leq\sigma_{m}\leq(\sigma_{N}-\sigma_{y})$
$\sigma_{max}-\sigma_{m}\geq\sigma_{N}$	$(\sigma_{N}-\sigma_{y})\leq\sigma_{m}\leq 0$
$\sigma_{max}-(1-r)\,\sigma_{m}\geq\sigma_{N}$	$0\leq\sigma_{m}\leq(\sigma_{y}-\sigma_{N})(1-r)$
$\sigma_{max}\geq\sigma_{y}$	$(\sigma_{y}-\sigma_{N})(1-r)\leq\sigma_{m}\leq\sigma_{y}$

with $r\equiv\sigma_{N}/\sigma_{u}$, σ_u is the tensile rupture limit.

Next, the creep time to rupture is extracted.

During complex uniaxial loading, different deterministic mathematical representations are based on peak-valley or range-mean matrix type to define groups of constant amplitude cycles, each with a fixed load amplitude and mean value. Such as cumulative exceeding curves (with the same reduction or counting of cycles) or sequential variable amplitude histories (usually the rainflow method of counting the cycles is preferred).

During each of these groups of constant amplitude cycles some "damage" is induced. Various rules are proposed to cumulate the "damage" Linear ones by Palgreen-Miner:

$$D_i=N_i/N_{Ri} \text{ and failure when } \sum D_i = 1,$$

(where N_i is the number of cycles realized during the cyclic loading i for which the number of cycles to rupture is N_{Ri}) or Non-linear ones such as those by Lemaitre-Chaboche.

The probabilistic representation (with the power spectra density to measure the load amplitude intensity in the frequency range) is often employed during random (stationary Gaussian) uniaxial loadings; it may be only combined with the linear cumulating rule for damage. Several experts are thinking that non Gaussian unixial loadings are more realistic and need special treatments.

During cyclic multi-axial loading (several loading parameters inducing out-of-phase stresses), the critical plane approach seems to be reasonable:

$$\gamma_{\max}(1+n\sigma_n^{\max}/\sigma_y)=(1+\nu)\,\sigma_f'\,/E(2N_f)^b+n/2(1+\nu)\,(\sigma_f')^2/E\sigma_y(2N_f)^{2b}+$$
$$+(1+\nu_p)\,\varepsilon_f'\,(2N_f)^c+n/2(1+\nu_p)\,(\sigma_f'\varepsilon_f')/\sigma_y(2N_f)^{b+c},$$

where $\gamma_{\max}$ is the maximum shear strain on the maximum shear strain amplitude plane; $\sigma_n^{\max}$ is the maximum stress normal to the maximum shear strain amplitude plane with the supplementary constitutive constants for the material; ν is the elastic Poisson ratio; σ_y is the elastic limit or yield stress; ν_p is the plastic Poisson ratio (0.5 for metals); n is a material constant to correlate the tensile data to the torsion data.

For non-cyclic multi-axial loadings, we shall only keep the simplest endurance criteria such that proposed by Dang Van or Kakuno-Kawada. Generally, it has the form:

$$C_a+\alpha P_a+\beta\quad P_{mean}<b,$$

where C_a is the deviatory stress amplitude P_a, the amplitude and P_{mean}, the mean value of the pressure (first invariant of the stress tensor); α , β and b are some phenomenological constants of the material.

The Dang Van's criterion is for example, written locally:

$$\Sigma\ eq = \tau\ (t)+a_{DV}.p(t) \leq b_{DV},$$

where $\tau(t)$ is the local shear stress on a critical slip plane, $p(t)$ is the local pressure and a_{DV} , b_{DV} are constants identified from endurance limits during alternate flexion and torsion tests.

These local quantities may be expressed from the global ones by making some simplifications:

$$I_E = nmax\ (tmax\{\ \|\ C_{alt}\|\ +a_{DV}.P(t)/b_{DV}\}\ ) < 1$$

where C_{alt} is the alternate part of the tangential stress and $P(t)$ is the global pressure.

But there are still many open problems:

– what is the validity of these Fatigue/Endurance criteria?

– what is the real physical meaning of the Damage parameter(s)?

– how to extract or represent of the random loading?

– the cumulation rules for Damage?

Indeed, it seems for us, that there is no difference between «GOD» with several religions and churches and DAMAGE with several models/theories and schools! That is why, we shall take all of them.

Intelligent representation of any loading. The most difficult part is to describe the loading. The main idea of the approach is to find an Equivalence rule between TWO loadings relative to «Damage» which may be used as a «Quantification» or norm of any loading relative to one particular structure made of particular materials. This rule needs to give a physical meaning of fatigue analysis during any loading and must allow for construction of simple and practical tools for fatigue analysis or accelerated fatigue tests. This representation has to be considered at the level of the materials and then at the level of the structure.

The materials have a Macroscopic behavior with its macroscopic elastic limit and workhardening modulus with which Direct or incremental analysis of the structure are performed. As only High cycles Fatigue is considered in this work, elastic shakedown of the structure is reached after some time.

But the materials have a Microscopic local behavior with its microscopic elastic or Endurance limit and local workhardening modulus. Although the global elastic shakedown, there is a local plastic shakedown.

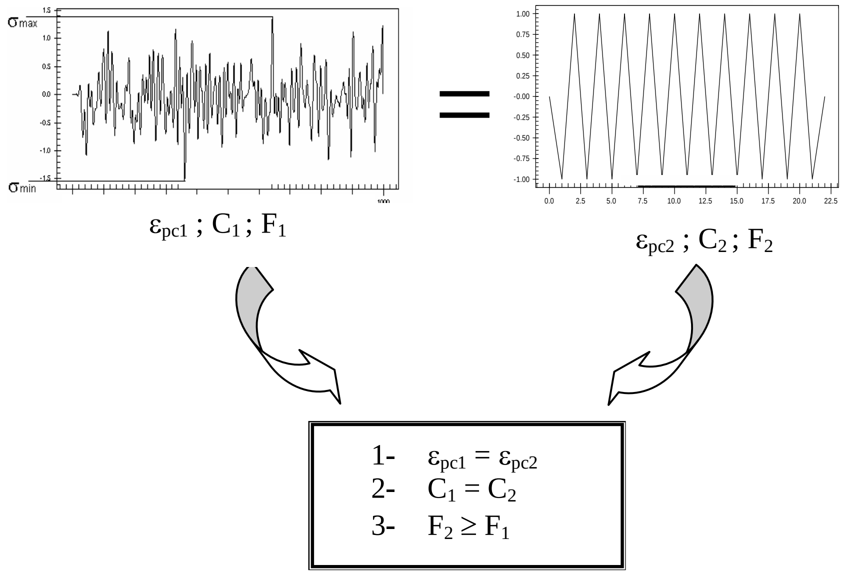
Level of the Material.

One parameter random loadings. Any one dimensional loading has its Center $C_0 = (\sigma_{max} + \sigma_{min})/2$, and fluctuation $F = (\sigma_{max} - \sigma_{min})/2$.

The local Cumulated plastic strain or local Dissipated energy during the real random loading is computed on the model representing the material such as, for example, the Kinematic Hardening behavior.

TWO LOADINGS ARE EQUIVALENT if they induce the SAME cumulative plastic strain (E_{pc}) or the SAME dissipated energy, they have the same center and almost the same fluctuation.

A particular family of cyclic loadings with a constant amplitude and a number of cycles may be deduced in Fig. 1.



similar to the "Wohler" curves ($F_2 = \Delta\sigma_k$, ΔN).

Fig. 1. A particular family of cyclic loadings with a constant amplitude and a number of cycles.

Multi-parameter random stress path. The same concept is used to define one equivalent radial cyclic loading to the general one: it will produce the same cumulated plastic strain, it will have the center and its fluctuation will be higher or equal the real fluctuation.

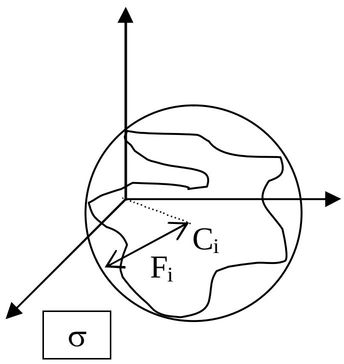
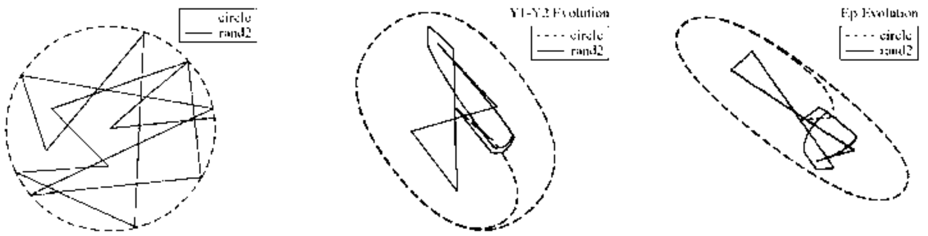


Fig. 2. Scheme “circular” stress path.

As we keep the fluctuation always the same, the range of microscopic plastic strains will be the same (to keep the same unknown damage mechanisms), as it may be seen in the figures: the response to any stress path is bounded by the "circular" stress path.



In the stress space In the transformed parameters space In the plastic strain space

Fig. 3. Species stress paths is bounded by the "circular" stress path.

Intelligent description of one general fatigue case. It is needed to transfer the primitive, passive descriptions of the geometry of structure, of its various material and of one block of its random loading parameters to an intelligent, active description such that the experimental results on one structure may be used to any other new one!

Here, in any point of the structure, the Output Primitive descriptors or conclusions are:

– failure or no failure;

– when there is failure, the number of blocks of the loading.

A multi-scale elastic analysis is considered, for example for a naval structure (Fig. 4):

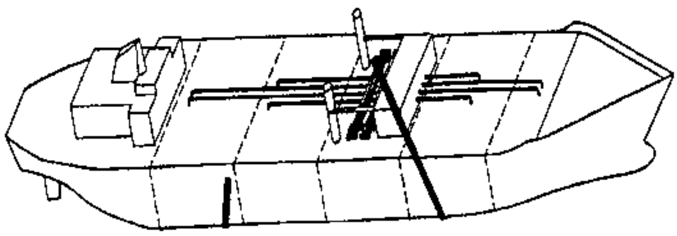
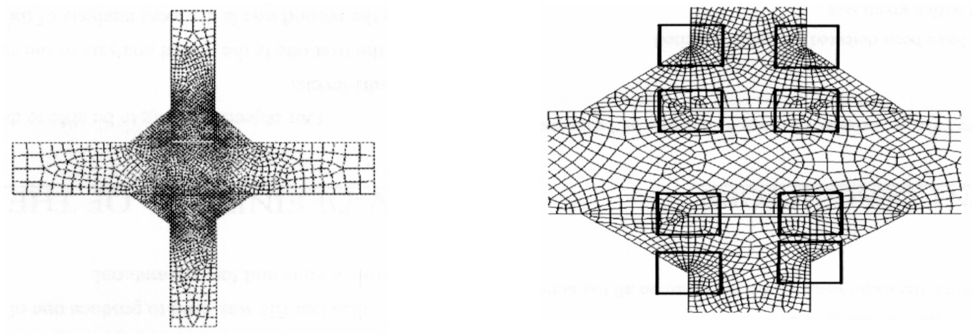


Fig. 4. Example for a naval structure.

1) at the scale of the hull with rather crude mesh (Fig. 5,*a*); elastic analysis is performed due to the various loadings;

2) then at the level of a substructure 3-D with a refined mesh (with the initial loading and the real loading, elastic, elastoplastic or simplified inelastic analysis are performed); the equivalent radial cyclic loading is characterized;

3) then at the scale of a 2-D detail (one slice by a plane of the substructure) with a much refined mesh (Fig. 5,*b*); a mobile window allows to focus at the different hot zones. The materials: base material, weld, and HAZ, are described from the material property database (smooth specimen data). The moving window is similar to a filter. Its size is such that the quantities which are needed become rather insensitive to the the errors associated to the mesh size and distribution.



a *b*

Fig. 5. Design scheme: *a* – with rather crude mesh; *b* – with a much refined mesh and mobile windows.

These quantities are related to the description of the stress and the gradient of this stress field. Among them, there are:

– the Maximum, Minimum and Average value of any field, such as I1 and J2, the Dang Van criterion ...;

– inside the window, volumes where any fatigue criterion is violated by a factor of 50%, 80% or 100%.

Generation of the design rules to fatigue

Available experimental data. All the experimental data used in the study are coming from the tests which were performed at the Illinois University. These tests were done in order to compare various design methods and to analyze the influence of some loading parameters and of the geometry on marine welded structures [4] (Fig. 6).

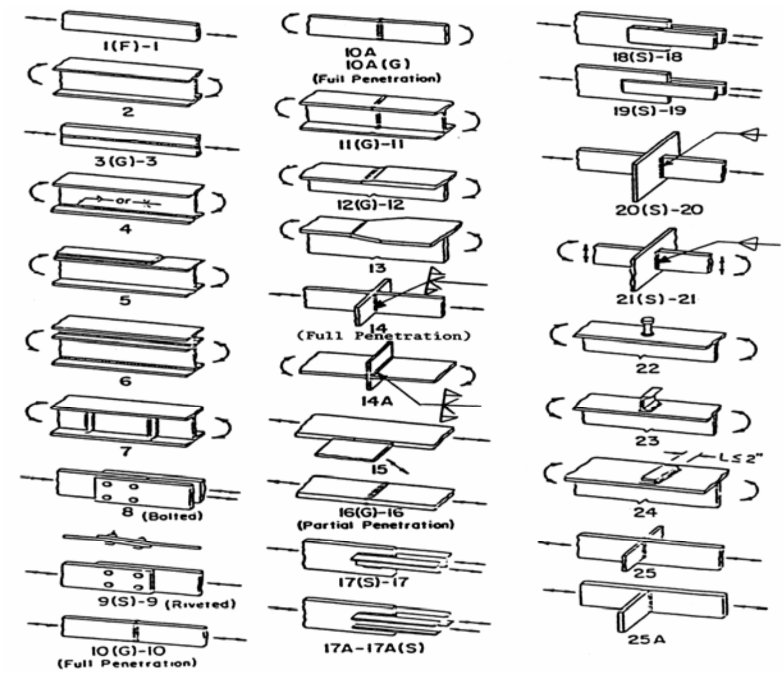


Fig. 6. Classical weld details [4].

Several structures, indeed several characteristical details were tested. They were selected among the classical ones in function of their relative importance. One the main details is the detail No. 20 (Fig. 7) which is also selected for its simplicity.

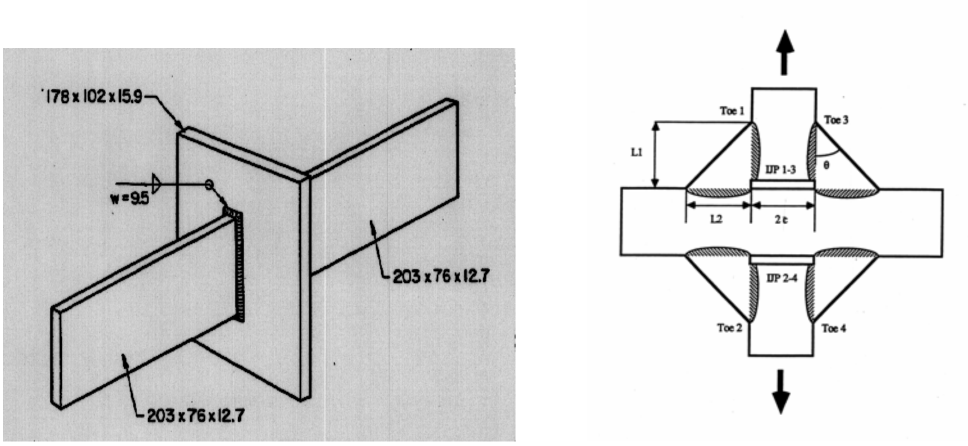


Fig. 7. Detail No. 20 with the critical points [4].

Within all details, three materials were mechanically characterized: the base metal, the weld and the HAZ heat affected zone.

Detail No. 20. It is made of one central plate on which two lateral plates are welded. Moreover the real geometry of the weld were measured. Twenty four specimens with three different plate thicknesses were tested.

Three thickness sizes of specimens were used in the experiments: 6.35, 12.7 and 25.4 mm for loading plates and 7.9, 15.9 and 31.8 mm for corresponding centre plates.

Three different materials were always considered: base material (for detail No. 20, ASTM A-36 steel), weld metal (with Shielded Metal Arc Welding method), heat affected zone.

The experimental set up in the tension-compression machine, implies that the grips induce important initial stresses which were measured thanks to four strain gages located in the vicinity of the weld on the lateral plates.

During each test, a fluctuating tensile load was applied: a mean stress level varying 0 and 144.5 MPa with a random amplitude block. (these stresses result from a long analysis on real naval structure). In principle, such a block was applied several times until one crack is initiated or the maximum number of 1500 times (which represents 125 years on the real structure). During the tests, special cares on the critical zones were taken, as these zones are the most sensitive to the crack initiation damage. For each sample, we have thus the geometry, the real loading, the place where cracks appear (but unhappily, the initial stresses due to the weld were not measured).

Modeling and Meshing with ALGOR. Script files for the design system SD3 from Algor were written to allow the systematical input of the geometry and the mesh of the specimen according the given experimental data. It was taken into account that 3 materials had to be differentiated.

The Heat Affected Zone was not perfectly described in the report. It was guessed according the other geometrical information. The system Algor proposes several mesh generators. For a 2D structure, it uses Supergen.

In order to take into account the different materials and to have a thinner mesh around the sensitive points, it is necessary to give some more information.

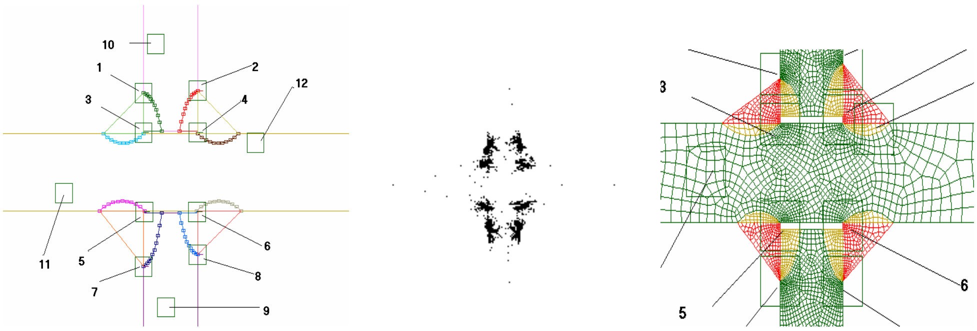


Fig. 8. Mesh and regions for 2D analysis Detail No. 20.

Elastic Analysis with NISA from EMRC. It is necessary to edit the nisa file within the preprocessor DISPLAY, to define the materials, the boundary conditions.

It is also necessary to introduce at first the initial stresses due to the grips and the misalignment. As underlined in the report, these stresses may be important although the care brought by the technicians.

It is, at last, necessary to define the loading on the specimen. For elastic only some unit loadings are introduced and then combined. For the elastoplastic analysis, the full time history of the loading is introduced.

Without giving details, we obtained the results for the 8 sensitive zones (IJP and TOE) and also for some 4 other randomly chosen zones within the specimen. The size of the zones or windows has been taken as a fundamental parameter of the study, 4 sizes were retained (1, 2, 4 and 8 mm).

The result of these analysis consists into the deduction of the initial stress field due to the grips and the applied stress field due to the random traction for each of the 12 regions and for each of the 3 differentiated materials.

Fatigue analysis with NISA. From these last results, it is possible to use the post processor ENDURE from EMRC. Only the crack initiation option of the program was used: the number of applied blocks necessary to induce fatigue in any point of the structure.

This last file was used to produce one of the intelligent descriptors, the mean value of the life taken on all the nodes within a zone and for one material.

Definition of the intelligent descriptors. As underlined all along this text, our objective being to be able to describe this detail 20 as any general structure. We have to make its analysis at 3 successive multi-levels:

1) the first one is the global analysis of the structure;

2) the second one is the local analysis of the critical details which have been detected as highly solicited;

3) the third one is at the level of the region i.e. a moving window with a given size.

These analysis have to be made with corresponding mesh sizes and some submodelling option where the results on the boundary of the coarse mesh are applied to the thinner mesh.

For us, one case, will consist at the particular behavior of one material within one actual window.

At our actual stage of analysis of the detail No. 20, we have performed already levels 2 and 3; it is now necessary to describe in an intelligent way the results obtained in each window for each material:

– the material characteristics during cyclic loadings, cyclic curves at different strain rate, Woehler curve and eventually also the rupture properties;

– the stress field with its evolution;

– some other factors such as given by the experts in fatigue/rupture or deduced from general tools such as ENDURE.

With such a description, the conclusions will be

– Failure or Not failure;

– if Failure, what is the fatigue life.

There are some natural methods to represent the material properties with some discrete parameters or descriptors.

The most difficult part is the representation of the evolution of the stress field which are here the initial stresses due to the welding (unknown in this study), the initial stresses due to the grips, and the applied random tensile load.

Material descriptors. We used only these 7 classical terms: (s_u) ultimate stress; (s'_y) elastic cyclic limit; (b) fatigue strength exponent; (c) fatigue ductility exponent; (n') cyclic hardening exponent; (k') coefficient cyclic strength coefficient; (s'_f) fatigue strength coefficient.

Stress field descriptors. At any given time, any scalar field M varying between M_{min} and M_{max} may be characterized with:

– the interval [M_{min}, M_{max}] is divided in n equal segments;

– the relative surfaces in the window for which the scalar M is included in the interval n, (S_n/S_0), where S_0 is the surface of the window.

In this study, we have taken n equal to 5 and we have assumed that the stress field at a given time is represented by I1, its first invariant, J2, the second invariant of its deviatoric part and the norm of the gradient of this J2 (the problem being the fatigue life).

It is also necessary to describe the evolution of the stress field with the time. Hablot [3] introduced:

– $\phi_1 = \mathrm{Sup}_t\ [M / \mathrm{Sup}_\Omega (M)]$ envelop during the time of the relative M (included between 0 and 1);

– $\phi_2 = \mathrm{Sup}_t\ [M]$ envelop along the time of the absolute value;

– $\phi_3 = r_r\ \mathrm{Sup}_t\ [\|\ \mathrm{grad}\ \{(M) / \mathrm{Sup}_\Omega (M)\}\ \|]$ envelop of the norm of the gradient of the relative equivalent stress. This field shows the location of the maxima of the gradient during the evolution;

– $\phi_4 = r_r\ \mathrm{Sup}_t\ [\|\ \mathrm{grad}\ (M)\ \|]$envelop of the norms of the absolute gradient. which expresses the most important gradients reached during the evolution;

– r_r is a characteristic dimension and many other quantities.

Although it was indicated in the Illinois report that the tensile load was a random load, during their tests, the real applied load was almost with a constant amplitude. We have then considered that it was sufficient for our study to characterize the stress field at 3 positions:

1) after the mean applied load;

2) at the maximum of the applied load;

3) at the minimum of the applied load.

57 descriptors are so introduced to represent the evolution of the stress field within the window.

Elasto-plastic analysis. The same samples with the same meshes but with a special loading path were analyzed. Indeed we added to the initial stress field due to the grip, the particular real load history as described in the report and we assumed that the stress field due to the welding (which is not known) was equal to zero.

As with all the samples, the elastic shakedown behavior was reached, we kept from the elastoplastic analysis, only the residual stress field which can then be treated as the initial stress field due to the grips during the elastic analysis.

The same intelligent descriptors were computed within the same windows around the same points in the specimens.

We also performed the incremental inelastic analysis during the random loading as decribed in the report and we considered the stress field at the end of the loading.

The execution times were very important with NISA.

The simplified inelastic analysis, ZAC was at last performed.

Data base and generation of the rules.

Compilation of data and automatic learning. Several details were tested. For each size of the window, several text files are induced. All these text files are merged. The observed conclusions are added. The data base has been so created. In the Excel files name1.xls , name2.xls, name4.xls and name8.xls, name10.xls the results of all the analysis corresponding to a window size of 1, 2, 4, 8 and 10 mm are given.

We recall that in our approach, each subregion i.e. one material in one region, is considered as an independent case/example for which we have its own intelligent descriptors and its two conclusions Failure or No failure and when there is failure, the number of cycles or number of blocks.

We used L.E.S. from the Ecole Polytechnique and Neuroshell from Wards systems to extract automatically the rules. Only the learning of Failure or No Failure has been done for the moment.

We also used the Probabilistic Neural Networks (PNN) which are able to train on sparse data sets and to separate data into a specified number of output categories.

Conclusions. From these results, the best window size has to be taken equal to 8 mm during the elastic analysis. Moreover, the simplified and elastoplastic analysis give almost the same reliability than the elastic one. Then only elastic analysis for any new structure with a window size of 8 mm have to be taken.

The rules which were generated on this detail, can now be used to analyze any other structure.

However, more experimental tests are still necessary to qualify fully our approach.

Comparaison between the reliabilities of the various learnings

File Des_Ela1Pro.out	**C1**	**C2**	**File Desc_zac1pro.out**	**C1**	**C2**
True positive proportion:	0.8381	0.9348	True positive proportion:	0.8730	0.9130
False positive proportion:	0.0652	0.1619	False positive proportion:	0.0870	0.1270
File Des_Ela2Pro.out	**C1**	**C2**	**File Desc_zac2pro.out**	**C1**	**C2**
True positive proportion:	0.8404	0.9796	True positive proportion:	0.8333	0.9388
False positive proportion:	0.0204	0.1596	False positive proportion:	0.0612	0.1667
File Des_Ela4Pro.out	**C1**	**C2**	**File Desc_zac4pro.out**	**C1**	**C2**
True positive proportion:	0.8003	0.9800	True positive proportion:	0.8312	0.9800
False positive proportion:	0.0200	0.1997	False positive proportion:	0.0200	0.1688
File Des_Ela8Pro.out	**C1**	**C2**	**File Desc_zac8pro.out**	**C1**	**C2**
True positive proportion:	0.8408	0.9800	True positive proportion:	0.8177	0.9200
False positive proportion:	0.0200	0.1592	False positive proportion:	0.0800	0.1823
File Des_Ela10Pro.out	**C1**	**C2**	**File Desc_zac10pro.out**	**C1**	**C2**
True positive proportion:	0.7392	0.9400	True positive proportion:	0.8333	0.9388
False positive proportion:	0.0600	0.2608	False positive proportion:	0.0612	0.1667
File Desc_cyc1pro.out	**C1**	**C2**	**File nDes_Ran1pro.out**	**C1**	**C2**
True positive proportion:	0.8770	0.9111	True positive proportion:	0.9280	0.9333
False positive proportion:	0.0889	0.1230	False positive proportion:	0.0667	0.0720
File Desc_cyc2pro.out	**C1**	**C2**	**File nDes_Ran2pro.out**	**C1**	**C2**
True positive proportion:	0.8710	0.9388	True positive proportion:	0.8737	0.8776
False positive proportion:	0.0612	0.1290	False positive proportion:	0.1224	0.1263
File Desc_cyc4pro.out	**C1**	**C2**	**File nDes_Ran4pro.out**	**C1**	**C2**
True positive proportion:	0.8771	0.9400	True positive proportion:	0.8886	0.8400
False positive proportion:	0.0600	0.1229	False positive proportion:	0.1600	0.1114
File Desc_cyc8pro.out	**C1**	**C2**	**File nDes_Ran8pro.out**	**C1**	**C2**
True positive proportion:	0.8035	0.9800	True positive proportion:	0.8359	0.9600
False positive proportion:	0.0200	0.1965	False positive proportion:	0.0400	0.1641
File Desc_cyc10pro.out	**C1**	**C2**	**File nDes_Ran10pro.out**	**C1**	**C2**
True positive proportion:	0.8402	0.9200	True positive proportion:	0.7380	0.9167
False positive proportion:	0.0800	0.1598	False positive proportion:	0.0833	0.2620

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Резюме

Разработан и описан специальный подход для анализа длительной усталости сварных конструкций при случайных многолетних аксиальных нагрузках, который имеет реальный физический смысл, и который очень легко выполнить. Основная идея заключается в том, чтобы найти подходящий эквивалент простой нагрузки, представить реальную случайную нагрузку с точки зрения повреждения на уровне материала и затем на уровне структуры.

Ключевые слова: усталостный анализ, структура, случайная нагрузка, программное обеспечение, сварные конструкции.

Резюме

Розроблено і описано спеціальний підхід для аналізу тривалої втоми зварних конструкцій при випадкових багаторічних аксіальних навантаженнях, що має реальний фізичний зміст, і який дуже легко виконати. Основна ідея полягає в тому, щоб знайти підходящий еквівалент простого навантаження, представити реальне випадкове навантаження з точки зору пошкодження на рівні материалу і потім на рівні структури.

Ключові слова: втомний аналіз, структура, випадкове навантаження, програмне забезпечення, зварні конструкції.

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