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PREDICTION DE LA DUREE DE VIE ADAPTEE AUX CHARGEMENTS MULTIAXIAUX D'AMPLITUDE VARIABLE

FATIGUE LIFE ASSESSMENT UNDER MULTIAXIAL VARIABLE AMPLITUDE LOADING

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SYNTHÈSE :

Cette note présente une nouvelle méthode de prédiction de la durée de vie en fatigue adaptée aux chargements multiaxiaux à amplitude variable. Cette méthode se fonde sur une approche en contrainte, les données d'entrée résultant d'un calcul ou provenant directement des sollicitations relevées en service. La méthode consiste à utiliser une variable de comptage (la contrainte normale sur un plan critique) pour identifier des cycles au sens de l'algorithme Rainflow, puis à utiliser une variable d'endommagement (construite à partir du taux de cisaillement alterné, de la contrainte normale et de la contrainte tangentielle au plan critique) pour évaluer le dommage de fatigue. La validation expérimentale de cette méthode est réalisée à partir d'essais biaxiaux d'amplitude variable réalisés sur des éprouvettes cruciformes au laboratoire d'Opole (Pologne).

EXECUTIVE SUMMARY :

A variable amplitude multiaxial fatigue life prediction method is presented in this paper. It is based on a stress approach as input data are the stress tensor histories which may be calculated by FEM analysis or measured directly on the structure during the service loading. The different steps of the method are first presented then its experimental validation is realized for long and finite fatigue lives through biaxial variable amplitude loading tests using cruciform steel samples.

FATIGUE LIFE ASSESSMENT UNDER MULTIAXIAL VARIABLE AMPLITUDE LOADING

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INTRODUCTION

Most mechanical components are usually submitted during their service to variable amplitude loadings. Economic constraints make for a decrease in the material weight used for any structure and consequently the stress level is increased. It is the reason why the fatigue phenomenon appears more and more often and has to be taken into account by engineering designers.

Classical methods deal either with uniaxial random loading or multiaxial constant amplitude loading. Anyway the most general case of loading is a multiaxial variable amplitude one. Until now few methods have been proposed for such a fatigue life prediction problem. This paper presents a stress-based approach available for multiaxial variable amplitude loading which is developed within the framework of partner relationship between Electricité de France and the Laboratory of Solids Mechanics of INSA - Lyon.

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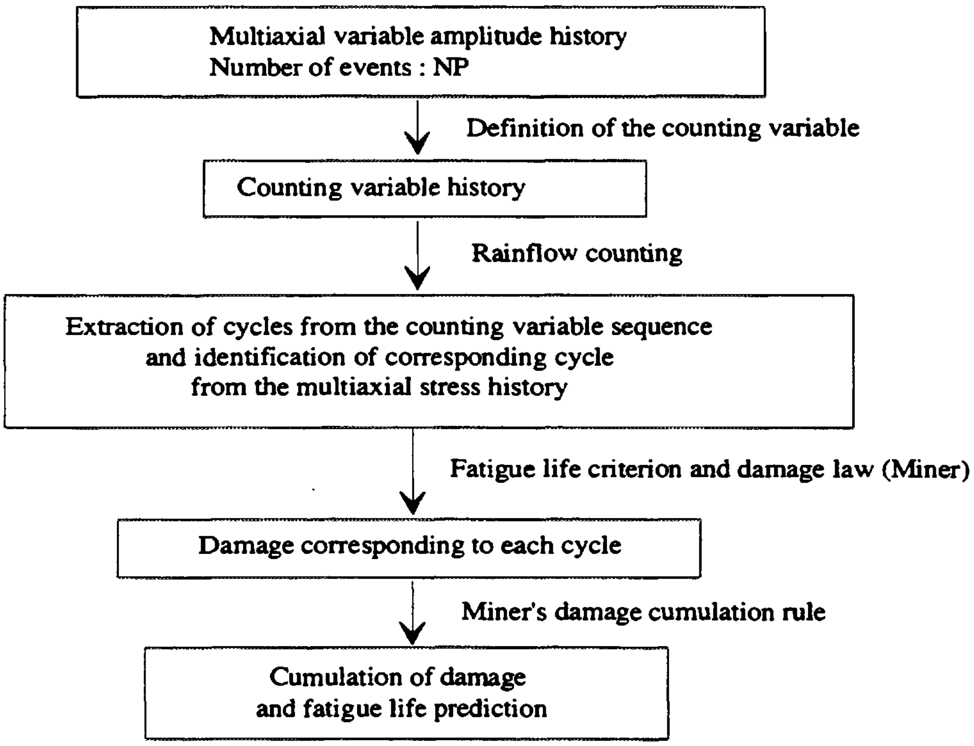
DESCRIPTION OF THE METHOD

The stress based approach which is proposed derives from an extension of long fatigue life criteria to finite fatigue lives (Robert (1)).The procedure keeps the main steps of uniaxial fatigue life prediction methods, as shown on the following flow chart (Robert and Bahuaud (2)) :



Flow chart of the proposed stress-based fatigue life prediction method

The final purpose of the method is to provide the fatigue life of the mechanical component, it is to say the number of sequences that can be applied up to crack initiation.

Given data are the multiaxial variable amplitude histories, i.e. the evolution of all the components of the stress tensor $[\sigma(t)]$ versus time t. These stresses may be obtained by Finite Elements Model or by direct measurements of strains on the component during its real service. All the steps deserve some explanations which are given in the following sections.

CYCLES COUNTING

Most fatigue life prediction methods require stress or strain cycles to assess the fatigue damage of any fatigue prone component. This is available both for elastic or plastic domain. A so called cycle counting method is then necessary to extract cycles. But cycles counting is rather more complex for multiaxial sequences. When many time series vary quite independently from each other, some cycles may appear on some channel but there is not generally such a corresponding cycle at the same moment on another channel (See figure 1). A stress cycle is identified for instance on channel $\sigma_{11}(t)$ between times t_1 and t_2 but there is not any cycle on the other channels $\sigma_{22}(t)$, $\sigma_{33}(t)$, $\sigma_{12}(t)$, $\sigma_{13}(t)$ and $\sigma_{23}(t)$ during this time interval (Vidal-sallé et al (3)).

A counting variable is consequently required. It must be good representative of the evolution of the stress tensor versus time and is rainflow counted. The choosen method is the one that is recommended by the French Association of Standardization (4). A previous work (1) has shown that different Rainflow counting algorithms, despite they seem to be quite similar, could provide very different fatigue lives. The strong influence of the procedure on the fatigue life prediction made a working group of SF2M (French Society of Materials and Metallurgy) issue the french standardization in 1993.

The proposed counting variable is the normal stress σ_{hh} that is acting on a physical plane P which is defined by its unit normal vector $\vec{h}$ (Kenmeugne (5)). Consider on this plane the stress vector $\vec{\phi}_h$, which is obtained by : $\vec{\phi}_h = [\sigma]\{\vec{h}\}$. $\vec{\phi}_h$ has a normal σ_{hh} and a shear τ_h components, which are obtained by projecting $\vec{\phi}_h$ on the straight line oriented by $\vec{h}$ and on the plane P respectively (See figure 2).

The choice of the physical plane is involved by the fact that the normal stress must not be constant when the stress tensor is changing, it is to say when its components are varying versus time t. The reason of that condition is contained in the algorithm of the Rainflow counting and is summarized on the figure 3. A cycle is identified by Rainflow counting method when the stress range between 2 consecutives peak and valley (transition BC), is less or equal to the range of the 2 transitions aside (ranges AB and CD). The cycle corresponds to the time interval $[t_1, t_2]$ and so is described by the evolution of $[\sigma_1(t)]$ between times t_1 and t_2.

FATIGUE LIFE PREDICTION

The fatigue life corresponding to a stress cycle is determined by the use of a fatigue criterion which formulation and applicability domain have been extended to limited fatigue life. Such an algorithm is based on the meaning of the difference between the value given by the fatigue criterion and the theoretical value (equal to unit) when the fatigue strength is reached. Any fatigue life criterion can be expressed according to the following relation :

$$E\left(\sigma_{ij}(t), \sigma_{-1}(N), \tau_{-1}(N), \sigma_0(N)\right) = 1 \tag{2}$$

where E is the fatigue function depending on the formulation of the criterion.

$\sigma_{-1}(N)$, $\tau_{-1}(N)$, $\sigma_0(N)$ are the three fatigue strengths of the material corresponding to N cycles and, a completely reversed tensile test, a completely reversed torsion test and a zero-to-maximum tensile test, respectively. We have $E = 1$ when the fatigue life of the cycle is equal to N cycles. Consequently $E < 1$ means that the fatigue life is greater than N cycles. And, on the contrary $E > 1$ means that the fatigue life is less than N cycles. An implicit algorithm allows to find the right fatigue life N_f up to crack initiation (Vidal et al (6)).

Our laboratory has proposed two different stress based multiaxial fatigue criteria. The first formulation is based on the Critical Plane Approach (CPA). A fatigue indicator $E_h(t)$ defined as a linear combination of the components of the stress vector acting on the surface element which normal unit vector is $\vec{h}$. These components are :

- the shear stress amplitude versus time (t) : $\tau_{ha}(t)$ (see figure 4),
- the normal stress amplitude versus time (t) : $\sigma_{hha}(t)$,
- the mean normal stress : σ_{hhm}.

The idea is to search the material plane on which the fatigue indicator E_h has the highest value. Its expression is :

$$E_h(t) = \left\|\vec{\tau}_{ha}(t)\right\| + \alpha(N) \cdot \sigma_{hha}(t) + \beta(N) \cdot \sigma_{hhm} \tag{3}$$

The fatigue function is then :

$$E_{CPA} = \frac{1}{\theta(N)} \max_{h,t}\left[E_h(t)\right] \tag{4}$$

where $\alpha(N)$, $\beta(N)$ and $\theta(N)$ are criterion parameters depending on the material fatigue strengths : $\sigma_{-1}(N)$, $\tau_{-1}(N)$, $\sigma_0(N)$.

This criterion is especially suitable in the case where principal stress directions remain fixed during the whole cycle because the most activated slipping plane is always the same (1).

The second criterion proposed by Fogue (7) has a global approach which derives from an idea of Simbürger (8). It is based on the root mean square of a fatigue indicator all over the possible surface elements through the calculation point M. The expression of the fatigue indicator is :

$$E_h = a(N) \cdot \max_t \left\| \vec{\tau}_{ha}(t) \right\| + b(N) \cdot \max_t \sigma_{hha}(t) + d(N) \cdot \sigma_{hhm} \tag{5}$$

where *a(N)*, *b(N)* and *d(N)* are parameters depending on $\sigma_{-1}(N)$, $\tau_{-1}(N)$ and $\sigma_0(N)$.

The fatigue function of the criterion is given by :

$$E_{GA} = \sqrt{\frac{1}{S} \int_S E_h^2 \cdot dS} \quad (6) \tag{6}$$

where S is the area of a sphere which radius is equal to unit ($S = 4\pi$).

This second criterion is more suitable when principal stress directions vary during the cycle because several slipping planes in this case are activated. The root mean square of the fatigue indicator is a way to take into account that physical phenomenon. Both criteria require to know or to model the three S-N curves $\sigma_{-1}(N)$, $\tau_{-1}(N)$, and $\sigma_0(N)$.

DAMAGE CALCULATION AND ITS CUMULATION

The damage corresponding to each extracted stress cycle is calculated by using Miner's rule and the fatigue life N_k that is given by the criterion.
The damage related to a cycle is given by :

$$d_k = \frac{1}{N_k} \tag{7}$$

Then the Miner linear damage summation technique gives the damage for the whole sequence by :

$$D = \sum_k d_k \tag{8}$$

Finally, the fatigue life corresponding to the whole sequence gives the number of sequences that can be applied to the structures up to crack initiation. It is obtained by :

$$\mathcal{N} = \frac{1}{D} \tag{9}$$

EXPERIMENTAL VALIDATION

The fatigue life assessment given by the proposed method is compared with experimental multiaxial variable amplitude tests results. These tests were carried out in the laboratory of Pr. Macha (Opole-Poland) on cruciform samples made of low carbon steel 10HNAP (Bedkowski (9)). Figures 5 and 6 give the shape of the samples and several details about the fatigue testing machine).

Two different multiaxial variable amplitude sequences are studied. The first one is composed of 178,260 events and the second one contains 190,410 events.

Experimental and numerical results are summarized in the following table.

	First sequence	Second sequence
Experimental fatigue life	1 300 sequences	1 663 sequences
Predicted fatigue life	670 sequences	585 sequences

The ratio between experimental and calculated fatigue lives is about 2.5 in both cases. Fatigue lives assessments are conservative ones.

CONCLUSION AND PERSPECTIVES

A fatigue life prediction method has been proposed for multiaxial variable amplitude loading. The procedure is today too time consuming to be available from an industrial point of view.

The perspectives of this work concern mainly numerical improvements to strongly reduce the calculation times on the one hand, and theoretical developments on the other hand. These are dealing with a better description of a high compressive mean stress in the criteria formulations, and also with the use of a non linear damage law (5).

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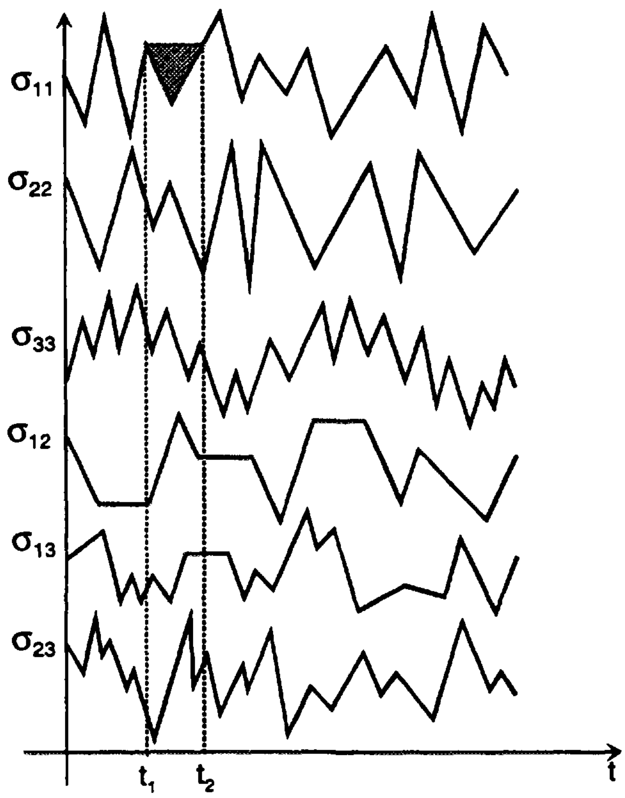

Figure1. Problem of cycles counting for multiaxial variable amplitude stress states

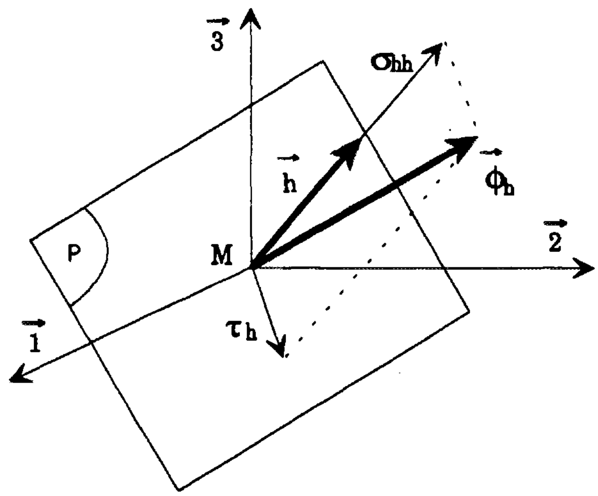

Figure 2. Definition of the stress vector acting on a physical plane.

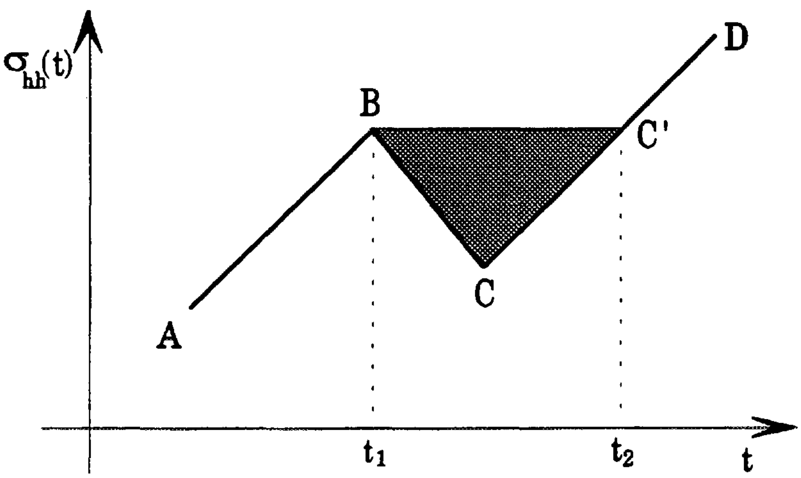

Figure 3. Rainflow counting principle

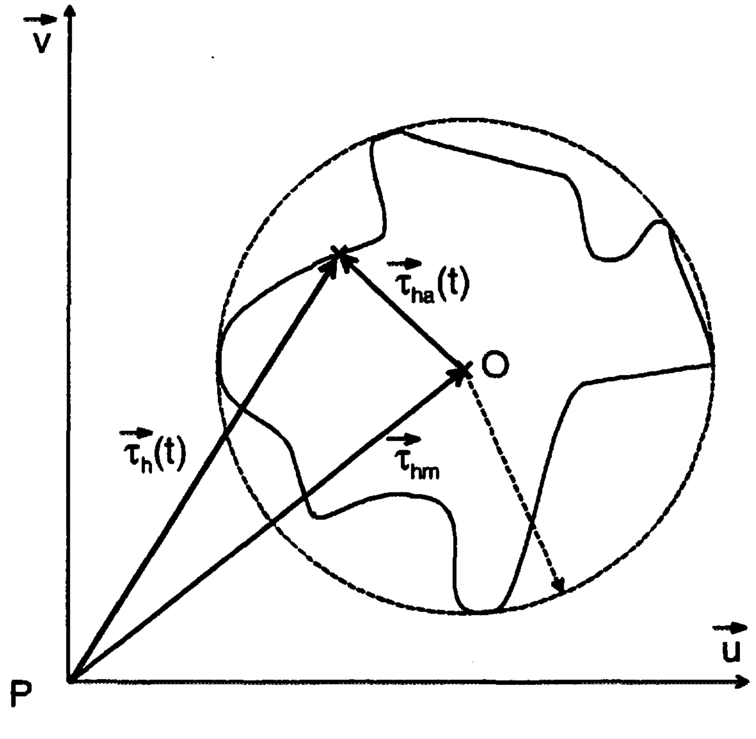

Figure 4. Definition of the shear stress amplitude

$\tau_{ha}(t) = \left\| \vec{\tau}_{ha}(t) \right\|$

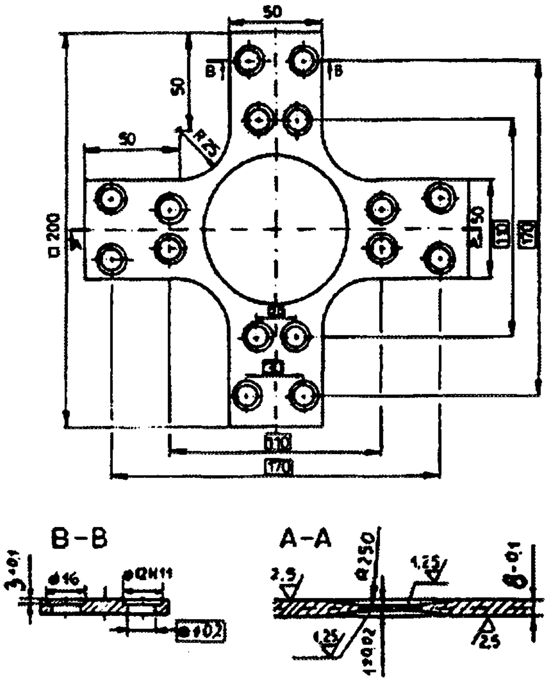

Figure 5. Cruciform Samples

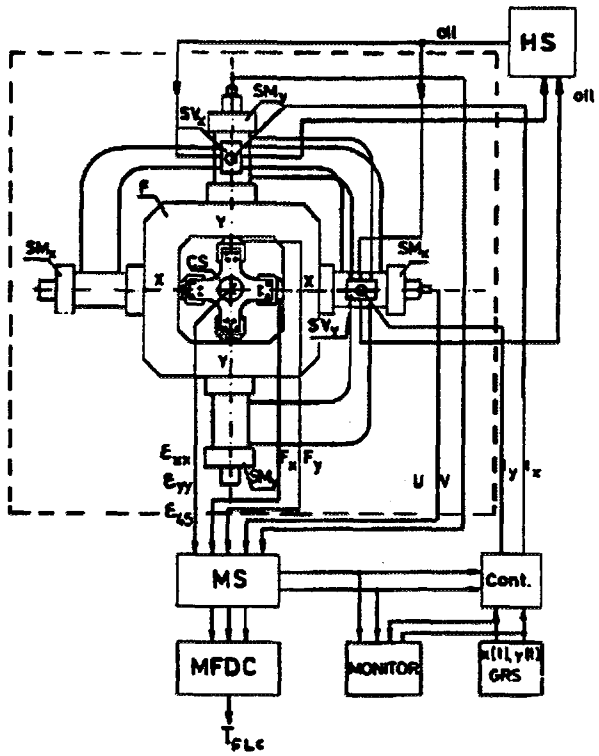

Figure 7. Experimental fatigue testing machine