Superposition of effects for the mechanical structures fatigue calculation

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1. Introduction

Initially, about 150 years ago, the problem of materials fatigue was raised in relation with loadings over 10^6 cycles, which corresponded to the life time of machines in those times (steam engines, components of railway etc.). Nowadays, some modern machines should be calculated for operation featuring gigacycle loadings:

- car engines, 10^8 cycles;

- railways for high speed trains, 10^9 cycles;

- gas turbines in aeronautics, 10^{10} cycles [1; 2].

On the other side, there is engineering equipment undergoing, throughout their life time, a relatively low number of loading cycles (under 10^3 ...10^4 cycles): chemical and petrochemical reactors, nuclear reactors etc.

Consequently, there have been developed calculation methods for life time expressed differently for a relatively low number of cycles, for a high or very high number of cycles:

- for a relatively low number of loading cycles, on the basis of dependence between strain amplitude, σ_a and the number of loading cycles, N;

-for a high but limited number of loading cycles, based on stress amplitude dependence, σ_a, and the number of loading cycles, *N*;

- for a high (unlimited) number of loading cycles by determining the interdependence between stress amplitude σ_a and average stress σ_m.

In the paper, based on the idea of effects superposition, one proposes: - a unique relation for the whole fatigue curve in order to evaluate fatigue strength, based on the dependence, σ_a (*N*)-σ_m; - a unique relation for calculating the effects superposition of several blocks of cyclic loadings, by also considering the influence of deterioration produced by preloading, corrosion etc.

In the case of variable loadings one discriminates the following problems involving effects superposition:

a. the total effect of normal stress loading which varies cyclically between σ_{min} and σ_{max} is transposed as stress amplitude effects superposition

$$\sigma_a = 0,5(\sigma_{max} - \sigma_{min}) \quad (1)$$

and mean stress

$$\sigma_m = 0,5(\sigma_{max} - \sigma_{min}) \quad (2)$$

or of elastic strains amplitude, ε_{ea} and viscous/plastic ε_{pa};

b. the total effect of a succession of variable loading blocks, ($\sigma_{a,1}$; $\sigma_{m.1}$); ($\sigma_{a,2}$; $\sigma_{m,2}$)…($\sigma_{a,i}$; $\sigma_{m,i}$)…, calculated as a function of partial effects;

c. the variable loadings are simultaneous, succeed or are succeeded by other loadings that deteriorate materials and mechanical structures. For example, the fatigue loading with residual stresses and/or cracks, in a corroding environment and/or creep conditions. etc. Or the fatigue load of a preloaded mechanical structure under certain conditions.

In-depth research has highlighted five domains on the curve σ_a - *N* (Figure 1), although actually, one considers only three domains, namely: *I* - loading with a reduced number of cycles ($N < N_y$) which is divided in sub domains I, a (N < 10^2) and I, b ($10^2 < N < N_y$); II - loading with a finite number of cycles ($N_y < N < N_0$) which covers sub domains II, a ($N_y < N < 10^5$) and II, b ($10^5 < N < N_0$) and III - loading with a great number of cycles ($N > N_0$) which is divided in sub domains III, a ($N = N_0$ ...10^8) and III, b (very high number of cycles, $N > 10^8$).

The value of N_0 depends on the nature of the material undergoing variable loadings. For example, $N = 10^6$ ... 10^7 - for steels and $N_0 = 10^8$ - for aluminum and its alloys.

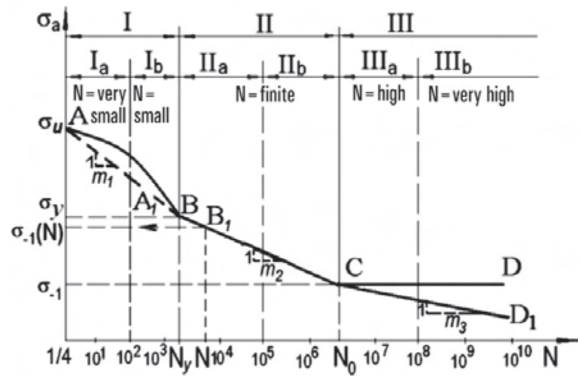

Figure 1. Dependence σ_a - *N* or fatigue curve (Wőhler curve) for steels (qualitative).

At $N \geq N_0$, one often considers that the diagramme is a straight-line CD, parallel to the abscissa corresponding to the fatigue limit σ_{-1}. At $\sigma_a \leq \sigma_{-1}$ one accepts that the sample has an infinite lifetime, which actually represents a convention imposed by economic considerations. Recent research has shown that most of the times when $N > N_0$, the material behaviour corresponds to the inclined straight line CD_1. In this latter case, one cannot define a fatigue limit. Consequently, the fatigue calculation when $N > N_0$ should be reconsidered for mechanical structures and modern machines which may even undergo loading megacycles. In some cases, the fatigue strength in the interval 10^6...10^9 cycles was reduced by 100 - 200 MPa [1; 2].

2. Behaviour laws of materials under fatigue loading with a single stress block

2.1. State of the art

On the basis of the fatigue behaviour law one may calculate the lifecycle expressed as the N number of loading cycles up to failure.

a. In domain I, where stress exceeds the yield stress, the material behaviour under monotonous loading is nonlinear. For this domain, there have been proposed several *empirical relations* which correlate strains in the plastic or plastic and elastic state with the number of loading cycles, N.

Several examples:

- Basquin-Coffin-Manson's law [3;4]

$$\varepsilon_a = \frac{\sigma'_f}{E} \cdot N^b + \varepsilon'_f \cdot N^c \tag{3}$$

where the first term in the right member represents the effect of elastic behavior, $\varepsilon_{e,a}$ while the second term corresponds to the plastic state behavior, $\varepsilon_{p,a}$. The graphic representation of relation (3) is shown in Figure 2, on which one can see the meaning of constants σ_f', ε_f' ; b and c in relation (3).

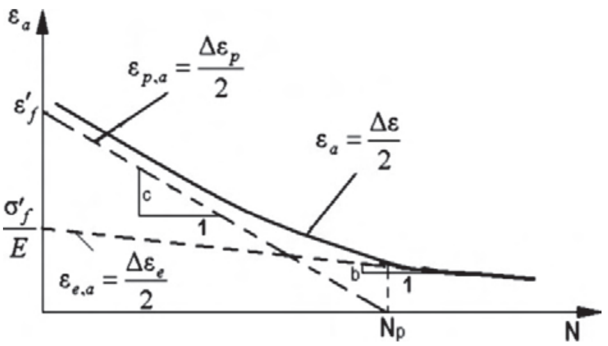

Figure 2. Dependence amplitude of total strain ε_a, on the number of loading cycles up to failure, *N*.

In order to highlight the influence of mean stress, σ_m , relation (3) has been corrected and there have been proposed:

- Morrow's law [5; 6],

$$\varepsilon_a = \frac{\sigma'_f - \sigma_m}{E} \cdot N^b + \varepsilon'_f \cdot N^c \tag{4}$$

- Manson - Halford's law [7],

$$\varepsilon_a = \frac{\sigma'_f}{E} \cdot \left(1 - \frac{\sigma_m}{\sigma'_f}\right) \cdot N^b + \varepsilon'_f \cdot \left(1 - \frac{\sigma_m}{\sigma'_f}\right)^{\frac{c}{b}} \cdot N^c \tag{5}$$

- Smith - Watson - Topper's law [8],

$$\sigma_{max} \cdot \varepsilon_a = \frac{\left(\sigma'_f\right)^2}{E} \cdot (N)^{2b} + \sigma'_f \cdot \varepsilon'_f \cdot (N)^{b+c} \tag{6}$$

- Chiou's law [9],

$$\sigma_{max}\left[\frac{\sigma_{max}}{E} + \left(\frac{\sigma_{max}}{k^*}\right)^{1/n^*}\right] = \frac{\sigma'_f}{E} \cdot (N)^{2b} + \sigma'_f \cdot \varepsilon'_f \cdot (N)^{b+c} \tag{7}$$

where the large brackets in the right member comes from Osgood - Ramberg's law, while the material constants K^* and n^* are different from those from monotonous loading.

Drawbacks of laws (3) - (8):

- although the materials behaviour in the plastic domain is nonlinear, one sums up algebraically the elastic and plastic deformations, which is not correct;

- some laws do not contain the influence of mean stress (for example (3)), while in others the mean stress was forcefully introduced, either in the right member ((4) and (5)), or the left one ((6) and (7)).

Since the relations of the ε_a - N type proposed at present feature a series of drawbacks, there has been recently proposed a relation similar to relation (3) on the basis of the energy concept, Jahed and Varvani - Farahani's law [10]

$$\Delta E_\sigma = E'_e \cdot N^B + E'_p \cdot N^C \tag{8}$$

where $\Delta E_\sigma = E_{\sigma, max} - E_{\sigma, min}$ is the specific energy range, E'_e; E'_p; B and C - material constants (Figure 3).

b. In domain II (Figure 1) one uses Basquin's law [11]

$$\sigma_a^m \cdot N = A \tag{9}$$

sometimes written as

$$\Delta\sigma^m \bullet N = A_1 \tag{10}$$

where A; A_1; m – material constants, while $\Delta\sigma_a = \sigma_{max} - \sigma_{min} = 2\sigma_a$ is the stress range.

This law does not include the influence of mean stress.

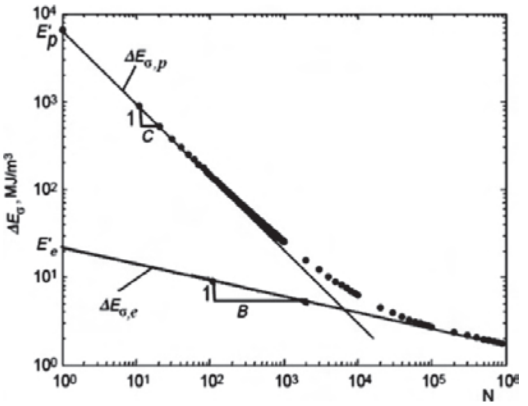

Figure 3. Dependence on N of strain energy under cyclic loading, ΔE_σ.

c. Domain III (Figure 1), considered until recently a domain of variable loading of unlimited duration, is defined by the straight line CD parallel to the abscissa, which defines the fatigue limit, σ_r, where $R = \sigma_{min}/\sigma_{max}$. Fatigue behaviour in this domain has often been represented in Haigh type diagrammes,

$$F(\sigma_a; \sigma_m) = 1 \tag{11}$$

For example, the behaviour laws presented in Table 1.

Some drawbacks of these laws:

- laws featuring the ratio σ_m/σ_c ar applicable only beyond the domain of plastic deformations;

- in relation (20) factor α_0 has no physical significance.

That is why, the curves which dependence σ_a/σ_{-1} de σ_m/σ_r extend up to values $\sigma_m/\ \sigma_r >> 1$. Or, at the limit, if l $\sigma_a = 0$, rupture occurs at $\sigma_m / \sigma_r = 1$.

2.2. A unique law for the whole fatigue curve

A unique law for the three domains of the fatigue curve may be obtained by describing the latter as a unique function dependent on stress amplitude, σ_a, on the material behaviour under monotonous loading (k) and the material fatigue behaviour ($\sigma_{a,cr}$ (N) and m):

$$P_\sigma\left[\frac{\sigma_a}{\sigma_{a,cr}(N)}; k; m\right] = C_\varepsilon \tag{22}$$

where $\sigma_{a,cr} = \sigma_{-1}(N)$. The right member should be a function dependent on the mean stress, σ_m, residual stress, σ_{rem}, crack size, a, previous deteriorations, D_σ , etc.

$$C_\sigma = F(\sigma_m; \sigma_{rem}; a; D_\sigma) \quad (23)$$

Since law (19) features a high degree of generality it should also be a *candidate for a unique relation*. Since law (19) was obtained theoretically, it depends on the material behaviour:

- under monotonous loading through relation:

$$\sigma = M_\sigma \bullet \varepsilon^k \quad (24)$$

where σ and ε are the natural stress and the natural strain; M_σ and k material constants;

- under fatigue loading through relation (9). In this case, by linearizing curve AB, in the domain I (Figure 1) the calculation becomes more safely.

Besides, as compared to the other known laws, law (19) takes into consideration:

- the sign of mean stress by means of factor

$$\delta_{\sigma_m} = \begin{cases} 1, \text{ if } \sigma_m > 0; \\ -1, \text{ if } \sigma_m < 0; \end{cases}$$

- loading rate, by means of exponent $\alpha = 1/k$, which, on first approximation may be considered [14; 15],

$$\alpha = \begin{cases} 1/k \text{ - if the cyclic loading is static in nature } (t_c \geq 12t_p); \\ 1/2k \text{ - if the cyclic loading is rapid } (t_c \in (2t_p;\ 12t_p)); \\ 0 \text{ - if the cyclic loading is by shock } (t_c \leq 2t_p), \end{cases}$$

where t_c is the duration of a loading cycle, while t_p - vibration period of the body under loading.

From relation (19), by particularization, one may obtain all the other relations from Table 1, where - in the observation column - one has inscribed the corresponding values of $\alpha = 1/k$ and $\sigma_{m,cr}$.

For the domains where diagram σ_a - N is an inclined straight line (I; II and CD1 in Figure 1), one replaces σ_{-1} with $\sigma_{-1}(N)$ - the sample fatigue strength after N loading cycles. With this notation, it follows that $\sigma_{-1} \equiv \sigma_{-1}(N_0)$.

Table 1. Behaviour laws for domain l III.

Nr.crt.	Behaviour Law	Author	Observation
1.	$\frac{\sigma_a}{\sigma_{-1}} + \left(\frac{\sigma_m}{\sigma_u}\right)^2 = 1$ (12)	W. Gerber (1874)	$\alpha = 0$ for σ_a/σ_{-1} ; $\alpha = 1$ for σ_m/σ_u ; $\sigma_{m,cr} = \sigma_u$.
2.	$\frac{\sigma_a}{\sigma_{-1}} + \frac{\sigma_m}{\sigma_u} = 1$ (13)	J. Goodman (1899)	$\alpha = 0$; $\sigma_{m,cr} = \sigma_u$.
3.	$\frac{\sigma_a}{\sigma_{-1}} + \frac{\sigma_m}{\sigma_y} = 1$ (14)	C.R. Soderberg (1930)	$\alpha = 1$; $\sigma_{m,cr} = \sigma_y$.
4.	$\frac{\sigma_a}{\sigma_{-1}} + \frac{\sigma_m}{\sigma_{cr,f}} = 1$ (15)	S.V. Serensen (1949)	$\sigma_{cr,f} = \frac{\sigma_0 \cdot \sigma_{-1}}{2\sigma_{-1} - \sigma_0}$ $\alpha = 1$; $\sigma_{m,cr} = \sigma_{cr,f}$.
5.	$\left(\frac{\sigma_a}{\sigma_{-1}}\right)^2 + \left(\frac{\sigma_m}{\sigma_y}\right)^2 = 1$ (16)	G. Buzdugan (1963)	- Proposed for metals [12]: $\alpha = 1$; $\sigma_{m,cr} = \sigma_y$.
6.	$\frac{\sigma_a}{\sigma_{-1}} + \frac{\sigma_m}{\sigma'_f} = 1$ (17)	J. Morrow (1968)	- For ductible steels: $\alpha = 1$; $\sigma_{m,cr} = \sigma'_f$.
7.	$\left(\frac{\sigma_a}{\sigma_{-1}}\right)^2 + \frac{\sigma_m}{\sigma_d} = 1$ (18)	Crawford and Benham (1974)	- Proposed for a plastic material [13]: $\alpha = 1$ for σ_a/σ_{-1} ; $\alpha = 0$ for σ_m/σ_d while $\sigma_{m,cr} = \sigma_d$.
8.	$\left(\frac{\sigma_a}{\sigma_{-1}}\right)^{\alpha+1} + \left(\frac{\sigma_m}{\sigma_{m,cr}}\right)^{\alpha+1} \cdot \delta_{\sigma_m} = 1$ (19)	V.V. Jinescu (1989)	$\alpha = 1/k$. Exponent $1/k$ comes from the behaviour law under monotonous loading $\sigma = M_\sigma \cdot \varepsilon^k$, where M_σ and k – material constants [14; 15].
9.	$\frac{\sigma_a}{\sigma_{-1}} = \exp\left(1 - \alpha_0 \cdot \frac{\sigma_m}{\sigma_u}\right)$ (20)	S. Kwofie (2001)	α_0 – numerical constant function of material sensitivity to mean stress [16].
10.	$\frac{\sigma_a}{\sigma_{-1}} + \left(\frac{\sigma_m}{\sigma_{-1}/\eta}\right) = 1$ (21)	G. Tao and Z.Xia (2007)	η is material constant. With $\sigma_{-1}/\eta = \sigma_u$ one obtains Goodman's law, while with $\sigma_{-1}/\eta = \sigma_y$ one obtains Soderberg's [17; 18].

σ_y –yield stress; σ_u – ultimate stress; σ_d – creep – rupture stress; σ_{-1} –fatigue limit with alternately symmetrical cycle; σ_0 –fatigue limit with pulsating cycle; $\sigma_{m,cr}$ – critical mean stress.

For real structures, with stress concentrators, featuring different sample sizes and surface quality, one will replace it with $\sigma_{-1,s}$ (N) which is the alternately symmetrical fatigue strength of the structure /piece after N loading cycles, defined according to relation:

$$\sigma_{-1,s}(N) = \frac{\varepsilon_d \cdot \gamma_s}{K_\sigma} \cdot \sigma_{-1}(N),$$

where ε_d is the dimensional factor; γ_s - quality coefficient of the piece surface; K_σ - stress concentration coefficient.

By applying Basquin's law (9) to points C and B_1 (Figure 1), for domain represented by straight line BC one obtains

$$\sigma_{-1}(N) = \sigma_{-1} \cdot \left(\frac{N_0}{N}\right)^{1/m} \qquad (25)$$

One deals in the same way with domains I (represented by straight line AA_1B) and III (represented by straight line CD_1) .

If we take into consideration the scattering of the experimental points, the dependence of the curves being traced on the likelihood of sample failure, the right member from relation (19) shall be replaced by a nondimensional variable P_{cr} which takes values between $P_{cr,min}$ (corresponding to the minimum acceptable failure probability) and $P_{cr,max} \leq 1$ (corresponding to the maximum accepted failure probability).

For a piece /structure, law (19) takes the following general form:

$$\left(\frac{\sigma_a}{\sigma_{-1,s}(N)}\right)^{\alpha+1} + \left(\frac{\sigma_m}{\sigma_{m,cr}}\right)^{\alpha+1} \cdot \delta_{\sigma_m} = P_{cr} \qquad (26)$$

Experiments have shown that, actually, one obtains a domain of the failure points through fatigue loading located between two *curves of constant life cycle corresponding* to $P_{cr,min}$ and $P_{cr,max}$ (Figure 4).

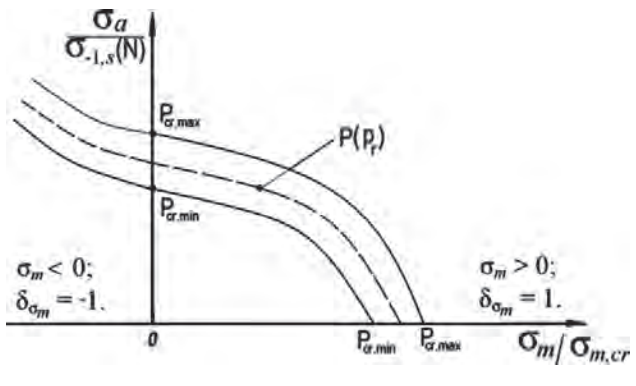

Figure 4. Domain where there are distributed the lifetime points corresponding to constants life under fatigue loading.

It follows that law (26) *has the highest degree of generality*: it takes into consideration the mean stress, statistic distribution of the material characteristics, the material nonlinear behaviour, as well as the difference between the real piece/structure and the sample.

The unique law (26) is applied to all the domains of the fatigue curve. The latter my be expressed analytically only through dependence σ_a - N, without making it necessary - as up to now- to express it through dependence ε_a - N (domains I and II,a), followed by the dependence based expression σ_a - N (domains II,b and III - curve CD_1).

3. Behaviour laws of the material under fatigue loading with several blocks of stresses

3.1. State of the art

The loading of a structure /piece under a succession of variable loading blocks (Figure 5) determines a succession of deteriorations. For the superposition of the effects of these loadings there have been proposed several empirical relations, generally based on summing up some of the reported durations without taking into consideration the different behaviour range of the materials - under and above, respectively - the yield stress.

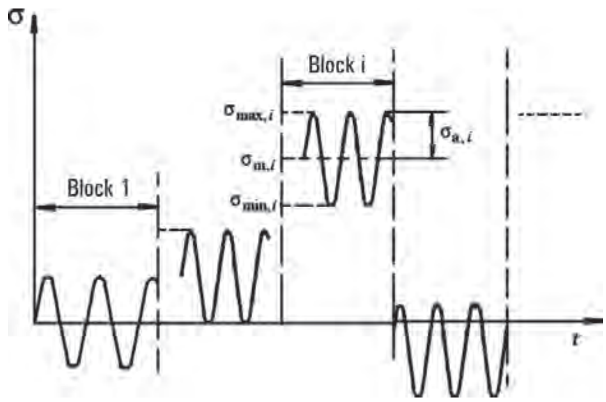

Figure 5. Variable loading under several blocks of normal stresses.

The first law proposed was Palmgren - Miner's empirical law [19; 20],

$$\sum_i \left(\frac{N}{N_{cr}}\right)_i = 1 \qquad (27)$$

although it was found that it had several drawbacks: it does not contain the influence of the material mean stress, of the cracks, of the residual stresses, of rupture or survival probability. In relation (27) N is the number of loading cycles with stress amplitude σ_a, while N_{cr} - value of under failure.

Despite these drawbacks in the ASME Code, Section VIII, Divison 3, the law is used as in (27), a deterministic form.

In order to correct these drawbacks in some design standards the right member from relation (27) is replaced with subunitary values. With this end in view, relation (27) is written as:

$$\sum_i \left(\frac{N}{N_{cr}}\right)_i = A \qquad (28)$$

In the design standard PD 5500, for example, one states that

$$A = 0{,}6 \cdot \left(\frac{22}{s}\right)^{0.75} \qquad (29)$$

where s is thickness in (in mm) of the fatigue loaded element. If $s < 22$ mm, one considers $s = 22$ mm, which makes it permanent that $A \leq 0.6$.

In the European standard EN-13445-3, in the calculation of equipment under pressure manufactured by welding,

$$A = \begin{cases} 0.8 - \text{for } N_{ech} \in [500;\ 1000); \\ 0.5 - \text{for } N_{ech} \in [1000;\ 10.000]; \\ 0.3 - \text{for } N_{ech} > 10.000 . \end{cases}$$

Because of the deviations from law (27) there were also proposed other empirical laws, namely: Marko - Starkey's law and modified Palmgren - Miner's law where an exponent different from one was introduced, though difficult to determine and not correlated with the material behaviour. Morrow [21] proposed relation (30) where there was introduced a correction dependent on the stress amplitude and an exponent, *d*, called, interaction exponent,

$$\sum_i \left[\left(\frac{N}{N_{cr}} \right)_i \cdot \left(\frac{\sigma_{a,i}}{\sigma_{a,\max}} \right)^d \right] = 1 \qquad (30)$$

All the drawbacks identified in relations (27) - (30) were removed by using the law theoretically established [22],

$$\sum_i \left(\frac{N}{N_{cr}} \right)_1^{\frac{\alpha+1}{m}} = 1 \qquad (31)$$

where $\alpha = 1/k$ while m is derived form Basquin's law (9) and takes different values in the three domains of the fatigue curve ($m = m_1$; m_2 *sau* m_3, Figure 1).

By taking into consideration the statistic scattering of the mechanical characteristics of the material, relation (31) is written under the general form

$$\sum_i \left(\frac{N}{N_{cr}} \right)_i^{\frac{\alpha+1}{m}} = P_{cr} \qquad (32)$$

where the critical participation P_{cr} has, in principle, the same meaning as the one in relation (26) and namely, it is a nondimensional variable, dependent on the mean stress, on the deterioration produced by the cracks and possible preloading, as well as the sample survival probability. The general expression of the critical participation

$$P_{cr} = P_{cr}(p_s) - \left(\frac{\sigma_m}{\sigma_r} \right)_{\max}^{\alpha+1} \cdot \delta_{\sigma_m} - D_T \qquad (33)$$

where σ_m is medium stress σ_u - ultimate stress; $(\sigma_m / \sigma_u)_{\max}$ - maximum value of this relation between loading cycles; δ_{σ_m} may take the values from rel. (19); $P_{cr}(p_s)$ is the initial critical participation (at $N = 1/4$) depending on the survival probability p_s. In the case of the deterministic definition of mechanical characteristics, $P_{cr}(p_s) = 1$.

The total deterioration D_T is a non dimensional variable which takes values between zero (virgin, undamaged material) and one (damaged material). It depends on the preloading and the action of some external factors such as corrosion, erosion, neutron flow, atomar hydrogen etc.

Because of the structure of the right member (33) of law (32) it is possible - that the latter might be sub unitary or super unitary which was also determined experimentally [20]. At the same time, the consideration of survival probability, p_s, makes the right member of relation (32) represent a statistic distribution with values between $P_{cr,min}$ and $P_{cr,max}$, because of the term $P_{cr}(ps) \in [(P_{cr})_{\min}; (P_{cr})_{\max}]$ where $(P_{cr})_{\min} > 0$ and $(P_{cr})_{\max} \leq 1$.

It follows that in the superposition of the effects of fatigue loading blocks, the highest degree of generality is held by the theoretical law (32) which takes into consideration the behaviour of the loaded material/structure, the deterministic definition of the mechanical characteristics of the material, the mean stress and the total deterioration D_T.

Law (32) applicable to fatigue loading under several blocks of stresses may be also extended to the case when other actions intervene, such as: preloading, crack existence, residual stresses, corrosion, erosion etc.

The influence of these actions is introduced into the expression of critical participation (33), by means of total deterioration D_T. With this aim in view one resorts to the principle of critical energy [23], based on which one can write the total deterioration as a sum of partial deteriorations:

$$D_T = D(-t) + D(a) + D(\sigma_{res}) + D(t_{cs}) \qquad (34)$$

where $D(a)$ is the deterioration produced by cracks with characteristic dimension a; $D(-t)$ – deterioration produced by preloading previous to calculation; $D(\sigma_{res})$ – „deterioration" produced by residual stress, σ_{rem}; $D(t_{cs})$ – deterioration produced by the corrosive action during t_{cs}.

Expressions for the partial deteriorations from relation (34) are obtained on the basis of the principle of critical energy [23].

Consequently, relation (32) where the right member is written as in (33), together with the precise data included in relation (34), represents a *general unique law* which allows the calculation of the lifecycle of a mechanical structure /piece under fatigue loading with several stress blocks, by considering the influence of mean stresses, the influence of the survival probability, the influence of the residual stresses, as well as the influences introduced into preloading, by the existence of corrosion/erosion.

4. Conclusions

From the analysis of the behaviour laws under fatigue proposed so far, the following drawbacks have resulted: - almost all the fatigue behaviour laws have been empirically deduced, or represent combinations of such laws.

No consideration was given to the material nonlinear behaviour, which is obvious in exceeding the yield stress. Consequently, for $\sigma > \sigma_y$, or $\varepsilon > \varepsilon_y$, the algebraic summation of effects is not correct.

By being empirically deduced, some of the relations do not contain the influence of the mean stresses, or the mean strains.

All the attempts at introducing the influence of the mean stresses resemble a hectic „grafting" based on empirical behaviour laws, laws that have limited validity. They are correct only for the set of experimental data they resulted form. Any extension beyond the particularities of these experiments is risky.

Based on the principle of critical energy by considering the nonlinear behaviour of the structure material, the paper has proposed:

- a unique law for the description of the whole fatigue curve (26);
- a general law for cumulating the effects in the case of cyclic loading under several stress blocks (32).

In the relations proposed one has taken into consideration the following: the nonlinear behaviour of the structure material, the mean stress, loading rate, deterioration produced by preloading, survival probability aso.

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