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A new strategy for fatigue analysis in presence of general multiaxial time varying loadings

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Abstract

The object of this paper is to propose an energy based fatigue approach which handles multidimensional time varying loading histories.

Our fundamental thought is to assume that the energy dissipated at small scales governs fatigue at failure. The basis of our model is to consider a plastic behavior at the mesoscopic scale with a dependence of the yield function not only on the deviatoric part of the stress but also on the hydrostatic part. A kinematic hardening under the assumption of associative plasticity is also considered. We also follow the Dang Van paradigm at macro scale. The structure is elastic at the macroscopic scale. At each material points, there is a stochastic distribution of weak points which will undergo strong plastic yielding, which contribute to energy dissipation without affecting the overall macroscopic stress.

Instead of using the number of cycles, we use the concept of loading history. To accommodate real life loading history more accurately, mean stress effect is taken into account in mesoscopic yield function and non-linear damage accumulation law are also considered in our model. Fatigue will then be determined from the plastic shakedown cycle and from a phenomenological fatigue law linking lifetime and accumulated mesoscopic plastic dissipation.

Keywords: Fatigue; Energy; High cycle; Plasticity; Mean stress

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Nomenclature

S_{max}	maximum deviatoric stress during the loading cycles
σ_{-1}	fatigue limit for fully reversed condition
b	back stress
\dot{w}	energy dissipation rate at a certain scale
\dot{W}	energy dissipation rate at all scales
W	dissipated energy
W_{cyc}	dissipated energy per cycle
N	current number of cycles
N_F	number of cycles to failure
$\dot{\varepsilon}_p$	rate of effective plastic strain
W_F	dissipated energy to failure per unit volume
E	Young's modulus
$k = 500 \sim 800 \text{ MPa}$	hardening parameter
$\beta = 1 \sim 50$	weakening scales distribution exponent
$\gamma = 0 \sim 50$	material parameter from Chaboche law(Wohler curve exponent)
$\alpha = 1 - a \left\langle \frac{\max_t \sqrt{J_{2,a}}(t) + a_c P_{max}(t) - b_c}{\sigma_u - 2 \max \sqrt{J_{2,a}}} \right\rangle$	characterizes non-linearity of damage accumulation
a	material parameter from Chaboche law
σ_y	macroscopic yield stress(normal or shear)
$\lambda = 0 \sim 5$	hydrostatic pressure sensitivity
$\underline{\underline{S}} = dev \underline{\underline{\Sigma}}$	deviatoric part of the stress tensor
Σ_H	macroscopic hydrostatic pressure
$A_{II} = \tau_{oct,a} = \sqrt{\frac{1}{3} J_{2,a}}$	the amplitude of octahedral shear stress
$S_{max} = \sigma_{VM} = \sqrt{6 J_{2,a}}$	Von Mises stress
s_{-1}	tensile fatigue limit for $R = -1$
$\langle \rangle$	Macaulay bracket symbol. $\langle \rangle$ is defined as $\langle m \rangle = 0$ if $m \leq 0$

1 Weakening scales and yield function

1.1. The concept of weakening scales

We follow the Dang Van paradigm. The structure is elastic at the macroscopic scale. At each material points, there is a stochastic distribution of weak points which will undergo strong plastic yielding, without contributing to the overall macroscopic stress. From a microscopic point of view, there is a distribution of weakening scales, namely $s \in [1, \infty)$. Let S_{max} be the macroscopic stress intensity at present time. Let σ_y be the yield limit before weakening. Then we imagine that for a given scale s :

- either $1 \leq s \leq \sigma_y/S_{max}$, then $S_{max} \leq \sigma_y/s$, the material stays in the elastic regime and there is no energy dissipation at this scale.
- or $\sigma_y/S_{max} \leq s \leq \infty$, then $S_{max} \geq \sigma_y/s$, the material is in the plastic regime and there is dissipated energy at scale s , contributing to the fatigue limit, which evolve through kinematic hardening.

In more details, at each scale s of a plastic evolution process there is a weakened yield limit σ_y/s , zero initial plastic strain $\underline{\underline{\varepsilon}}_p$ and zero initial backstress $\underline{\underline{b}}$ at initial time t_0 .

1.2. Distribution of weakening scales

We assume the weakening scales have a probability distribution of power law:

$$P(s) = Cs^{-\beta},$$

where β is a material constant and C is hardening constant. The choice of a power law has two reasons: on one hand, this type of distribution corresponds to a scale invariant process, on the other hand it leads in cyclic loading to a prediction of a number of cycles to life limit as a power law function of the stress intensity. More general laws can also be proposed.

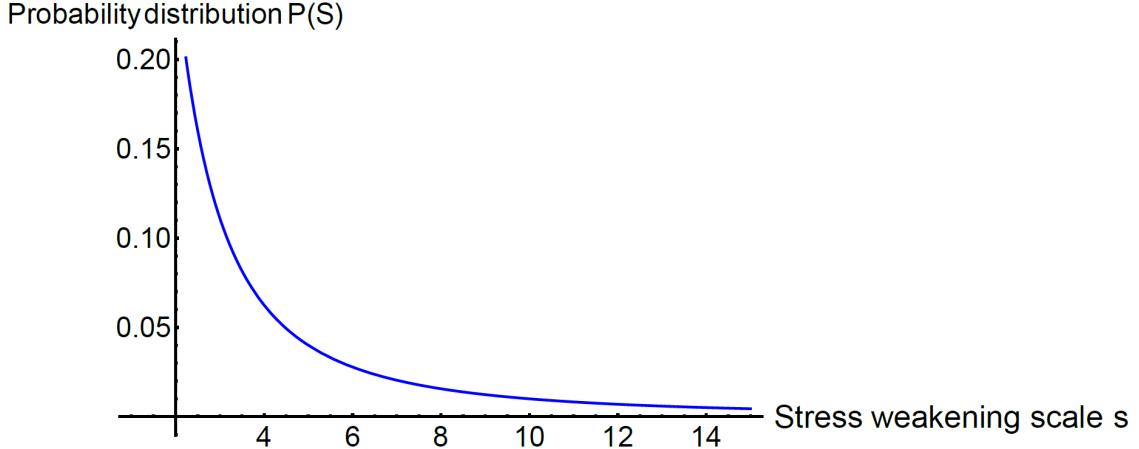
The integrated probability ranging from macroscopic to microscopic stress is unity. From this we can conclude:

$$\int_1^\infty P(s)ds = \left[\frac{Cs^{1-\beta}}{1-\beta} \right]_1^\infty = 0 - \frac{C}{1-\beta} = 1.$$

Then we know $C = \beta - 1$, so the distribution is given by:

$$P(s) = Cs^{-\beta} = (\beta - 1)s^{-\beta}$$

and it is shown in Figure 1.

Figure 1: Weakening scales s probability distribution curve

1.3. Yield function with mean stress effect

Positive mean stress clearly reduces the fatigue life of the material. In design evaluation of multiaxial fatigue with mean stress, a simplified, conservative relation between mean stress and equivalent alternating stress is necessary. We can improve the model by modifying the yield function σ_y and the localization tensor.

The idea is to consider as in Maitournam and Krebs[1] that the yield limit σ_y can be reduced in presence of positive mean stress. The mesoscopic yield function can therefore be written as:

$$f(s) = \|\underline{\underline{S}}(s) - \underline{\underline{b}}(s)\| + (\lambda \Sigma_H - \sigma_y) / s \leq 0 \quad (1)$$

with $\underline{\underline{S}}$ denoting the deviatoric part of the stress tensor at microscale, and $\underline{\underline{b}}(s)$ the corresponding backstress at the same scale. The material remain in elastic regime when $f < 0$ and in plastic regime when $f = 0$.

1.4. Local plastic model

First we should describe the mesoscopic stress state. The model considers a plastic behavior at the mesoscopic scale. The mesoscopic evolution equations are thus:

$$\dot{\underline{\underline{S}}}(s, M, t) = \text{dev} \dot{\underline{\underline{\Sigma}}}(M, t) - \frac{E}{1 + \nu} \dot{\underline{\underline{\varepsilon}}}^p(s, M, t), \quad (2)$$

which defines a Taylor-Lin scale transition model with unit localization tensor[2].

$$\dot{\underline{\underline{b}}}(s, M, t) = \frac{kE}{E - k} \dot{\underline{\underline{\varepsilon}}}^p(s, M, t), \quad (3)$$

which is our kinematic hardening model.

$$\dot{\underline{\underline{\varepsilon}}}^p(s, M, t) = \gamma \frac{\partial f(s, M, t)}{\partial \underline{\underline{S}}}, \quad (4)$$

which is the associated plastic flow rule assuming $\gamma = 0$ when $f < 0$ and $\gamma \geq 0$ when $f = 0$.

Here E denotes the Young's modulus and k the hardening parameter. The local dissipated energy rate per volume at weakening scales s is given by the local entropy dissipation:

$$\dot{w}(s, M, t) = (\underline{S} - \underline{b})(s, M, t) : \dot{\underline{\varepsilon}}^p(s, M, t). \quad (5)$$

2 Construction of an energy based fatigue approach

In a preliminary step, we will consider a simple macroscopic loading history $\underline{\Sigma}(M, t)$ which is uniaxial and time periodic of deviatoric amplitude S_{max} , and a Von Mises flow rule to see if we get a prediction of local failure for a number of cycles N_F varying as $\Sigma^{-\beta}$.

In uniaxial cyclic loading, there will be 3 kinds of loading patterns, as is shown in Figure 2:

1. Elastic regime, in phase 2 and 4, where $\dot{\underline{\varepsilon}}^p(s, M, t) = 0$, and $|\underline{S} - \underline{b}| < (\sigma_y - \lambda \Sigma_H) / s$.
2. Plastic regime according to plastic flow rule, with increasing plastic deformation, in phase 5 and 1, where $\dot{\underline{\varepsilon}}^p(s, M, t) = \gamma \frac{\underline{S}(s) - \underline{b}(s)}{\|\underline{S}(s) - \underline{b}(s)\|} > 0$ with $\gamma = (dev \dot{\Sigma}) \left(\frac{kE}{E - k} + \frac{E}{1 + \nu} \right)^{-1}$, with $\underline{S} - \underline{b} = (\sigma_y - \lambda \Sigma_H) / s$ and $\dot{\underline{S}} - \dot{\underline{b}} = 0$.
3. Plastic regime in the other direction, in phase 3, there is $\dot{\underline{\varepsilon}}^p(s, M, t) < 0$, then $\underline{S} - \underline{b} = -(\sigma_y - \lambda \Sigma_H) / s$ and $\dot{\underline{S}} - \dot{\underline{b}} = 0$

In phase 1, a direct analysis yields the energy dissipation at scale s :

$$dW = (S - b) d\varepsilon^p = \frac{(E - k)(1 + \nu)}{E(E + kv)} \frac{\sigma_y - \lambda \Sigma_H}{s} \left(S_{max} - \frac{\sigma_y - \lambda \Sigma_H}{s} \right) \quad (6)$$

A similar analysis yields

$$dW(\text{phase1}) = dW(\text{phase5}) = \frac{1}{2} dW(\text{phase3}).$$

We can then calculate the local dissipated energy W at point M during one cycle by cumulating the input of all sub-scales which result in plastic regime with their probabilities [3].

$$\begin{aligned} W_{cyc} &= 4 \int_{(\sigma_y - \lambda \Sigma_H) / S_{max}}^{\infty} dW(s, M, t) P(s) ds \\ &= 4 \int_{(\sigma_y - \lambda \Sigma_H) / S_{max}}^{\infty} \frac{(E - k)(1 + \nu)}{E(E + kv)} \frac{\sigma_y - \lambda \Sigma_H}{s} \left(S_{max} - \frac{\sigma_y - \lambda \Sigma_H}{s} \right) (\beta - 1) s^{-\beta} ds \\ &= \frac{4(E - k)(1 + \nu)(\beta - 1)}{E(E + kv)\beta(\beta + 1)} \frac{S_{max}^{\beta + 1}}{(\sigma_y - \lambda \Sigma_H)^{\beta - 1}}. \end{aligned} \quad (7)$$

If the dissipated energy accumulates linearly until a failure value W_F , we can get directly the time to failure from Eq.(8):

$$T_{fail} = N_F t_{cyc} = \frac{W_F}{W_{cyc}} t_{cyc} = C (S_{max})^{-\beta - 1}. \quad (8)$$

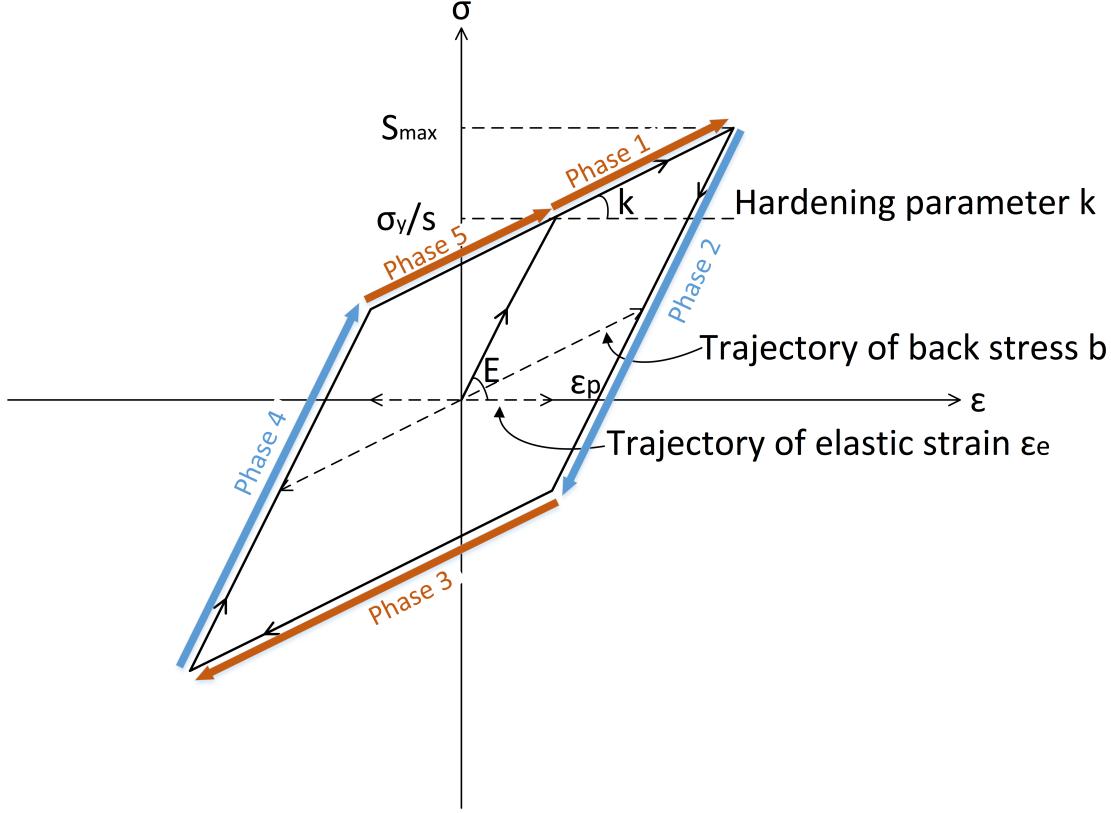


Figure 2: Uniaxial load with plastic dissipation

From Eq.(7), we then obtain that the model predicts as expected a power law dependence in function of S_{max} . However, experiments shows that the damage or the energy accumulation of a material evolves non-linearly in time. We should introduce below a method to handle such a nonlinearity.

3 Nonlinearity of damage accumulation

3.1. Energy approach with Chaboche law

The Chaboche law[4] is essentially a damage incremental law for cyclic loading of stress intensity σ with a deviatoric part A_{II} and hydrostatic part Σ_H , defining the damage increase by:

$$\delta D = (1 - (1 - D)^{\gamma+1})^\alpha \left(\frac{A_{II}/(1 - D)}{M(\Sigma_H)} \right)^\gamma \delta N \quad (9)$$

which writes equivalently as Eq.(10)

$$\delta[1 - (1 - D)^{\gamma+1}]^{1-\alpha} = (1 - \alpha)(\gamma + 1) \left(\frac{A_{II}}{M(\Sigma_H)} \right)^\gamma \delta N = \frac{\delta N}{N_F(\sigma)}. \quad (10)$$

Here $N_F(\sigma)$ denotes the number of cycles at intensity σ to failure as obtained by integration of Eq.(10) from $D = 0$ to $D = 1$.

In our model, in case of a simple uniaxial cyclic loading, we propose to replace $\frac{1}{N_F(\sigma)}$ which is the relative unit increment of cycles by $\frac{W_{cyc}}{W_F}$, yielding the nonlinear damage incremental law:

$$\delta[1 - (1 - D)^{\gamma+1}]^{1-\alpha} = \frac{W_{cyc}}{W_F} \delta N. \quad (11)$$

This is a nonlinear law but used with a constant α , there will be no sequence effect. In other words, when applying two successive cycles of different intensities, the failure will occur at the same number of cycles whatever the order of the loading (high then low versus low then high).

3.2. Generalized damage accumulation

Formula (10) is a general accumulation law which can be applied for any cyclic loading sequence provided that we can identify the multiscale value of the dissipated energy per cycle.

But the notion of cycle itself may be hard to identify for general loadings. The idea is then to replace the relative increment of dissipated energy per cycle by the relative increment of dissipated energy per unit time, yielding:

$$\delta[1 - (1 - D)^{\gamma+1}]^{1-\alpha} = \frac{\dot{W}}{W_F} \delta t. \quad (12)$$

In a general loading case, \dot{W} is to be computed. By integrating Eq.(5) over all microscales, we get:

$$\dot{W}(M, t) = \int_{s=1}^{\infty} \dot{w}(s, M, t) P(s) ds = \int_{s=1}^{\infty} \left(\underline{S} - \underline{b} \right) (s, M, t) : \underline{\dot{\epsilon}}^p(s, M, t) P(s) ds. \quad (13)$$

The evolution of \underline{S} , \underline{b} and $\underline{\dot{\epsilon}}^p$ are given in section 1.4. Equation (12) and (13) are therefore our proposed damage law.

4 Loop on time and scales

4.1. Integration rules for \dot{W} and δD

Our first approach takes one cycle as unit time. We compute analytically the energy dissipation at each scale during this cycle. The method is valid for simple loading history and which includes the integration on all weakening scales. The damage D is accumulated after each cycle.

However, there are certain limitations of this method. Firstly we need a load history decomposition in cycles. Secondly in real life the perfect close loop cycle is hardly applicable.

Thus we propose in Eq.(12) a more general method which can be integrated by a step by step strategy. We compute numerically the dissipation at different scales using an implicit Euler time integration of the

constitutive laws of section 1.4. After which we make a numerical integration on different scales. Then we can update the damage and go to next time step.

Instead of doing the scale integration directly which can be difficult for complex loading, the Gaussian Quadrature rule with Legendre points is used to give the value of local dissipated energy rate.

To use the Gaussian quadrature rule the limit range of integral must be from -1 to 1 , while the total dissipated energy is expressed by integrating all the weakening scale s ranging from 1 to infinity with their occurrence probabilities:

$$\dot{W} = \int_1^\infty \dot{w}(s)(\beta - 1)(s)^{-\beta} ds.$$

To change the limit range of integral from $[1, \infty]$ to $[1, 0]$ we take as new integration variable $u(s) = s^{-p}$ with $p = \beta - 1$, yielding $u(1) = 1$ and $u(\infty) = 0$ with

$$du = -ps^{-p-1} ds$$

that is

$$du = (-\beta + 1)s^{-\beta} ds = (-\beta + 1)s^{-\beta} ds.$$

Therefore the dissipated energy summed on all scales is:

$$\begin{aligned} \dot{W} &= \int_1^\infty \dot{w}(s)(\beta - 1)(s)^{-\beta} ds \\ &= \int_1^0 \dot{w}(u^{\frac{1}{1-\beta}})(\beta - 1) \frac{1}{-\beta + 1} du \\ &= \int_0^1 \dot{w}(u^{\frac{1}{1-\beta}})(\beta - 1) \frac{1}{\beta - 1} du \\ &= \int_0^1 \dot{w}(u^{\frac{1}{1-\beta}}) du \\ &= \frac{1}{2} \int_{-1}^1 \dot{w}\left[\left(\frac{x+1}{2}\right)^{\frac{1}{1-\beta}}\right] dx \end{aligned} \quad (14)$$

if we set $u = \frac{x+1}{2}$.

So the dissipated energy rate integrated over all scales takes the form of Eq.(15):

$$\dot{W} = \frac{1}{2} \int_{-1}^1 \dot{w}\left[\left(\frac{x+1}{2}\right)^{\frac{1}{1-\beta}}, t\right] dx \approx \frac{1}{2} \sum_i \omega_i \dot{w}\left[\left(\frac{x_i+1}{2}\right)^{\frac{1}{1-\beta}}, t\right], \quad (15)$$

where ω_i and x_i are respectively the weights and nodes of the Gauss Legendre integration rule used for the numerical integration. In this work, we used 25 points[5].

After changing the integration limit, $\left(\frac{x+1}{2}\right)^{\frac{1}{1-\beta}}$ represents the weakening scale s .

Damage accumulation is deduced from Eq.(12):

$$g_{n+1} = g_n + \frac{\dot{W} dt}{W_F} \quad (16)$$

with $g_n = [1 - (1 - D_n)^{\gamma+1}]^{1-\alpha}$.

We upgrade the damage step by step following Eq.(16). When D reaches one, the material fails.

4.2. Regime determination under multiple scales

The material could be both in elastic and plastic regime at different scales. To be more elaborate, we reuse the fundamental equations in different regimes. At scale s , we have a dissipation rate given by:

$$\dot{w}(s) = \left(\underline{\underline{S}} - \underline{\underline{b}} \right) : \dot{\underline{\underline{\varepsilon}}}^p,$$

which differs between plastic and elastic regime.

Elastic regime:

There we have $\dot{\underline{\underline{\varepsilon}}}^p = 0$, $\dot{\underline{\underline{b}}} = 0$ and $\dot{\underline{\underline{S}}} = dev\dot{\underline{\underline{\Sigma}}}$, so

$$\dot{\underline{\underline{S}}} - \dot{\underline{\underline{b}}} = dev\dot{\underline{\underline{\Sigma}}},$$

yielding

$$\left(\underline{\underline{S}} - \underline{\underline{b}} \right) (t + dt) = \left(\underline{\underline{S}} - \underline{\underline{b}} \right) (t) + dev\dot{\underline{\underline{\Sigma}}} dt := \left(\underline{\underline{S}} - \underline{\underline{b}} \right)_{trial} (t + dt). \quad (17)$$

We are in elastic regime at scale s as long as we satisfy

$$\left(\underline{\underline{S}} - \underline{\underline{b}} \right) (t + dt) \leq (\sigma_y - \lambda \Sigma_H) / s.$$

Plastic regime:

When we leave elastic regime at scale s , we have:

$$\left\{ \begin{array}{ll} \dot{\underline{\underline{\varepsilon}}}^p = \gamma \frac{\underline{\underline{S}} - \underline{\underline{b}}}{\| \underline{\underline{S}} - \underline{\underline{b}} \|}, \gamma > 0, & \text{plastic flow,} \\ \| \underline{\underline{S}} - \underline{\underline{b}} \| = (\sigma_y - \lambda \Sigma_H) / s, & \text{yield limit,} \\ \left(\underline{\underline{S}} - \underline{\underline{b}} \right) : \left(\dot{\underline{\underline{S}}} - \dot{\underline{\underline{b}}} \right) = 0, & \text{yield limit time invariance,} \\ \dot{\underline{\underline{b}}} = \frac{kE}{E - k} \dot{\underline{\underline{\varepsilon}}}^p, & \text{kinematic hardening rule,} \\ \dot{\underline{\underline{S}}} = dev\dot{\underline{\underline{\Sigma}}} - \frac{E}{1 + \nu} \dot{\underline{\underline{\varepsilon}}}^p, & \text{localisation rule.} \end{array} \right. \quad (18)$$

$$\left\{ \begin{array}{ll} \dot{\underline{\underline{\varepsilon}}}^p = \gamma \frac{\underline{\underline{S}} - \underline{\underline{b}}}{\| \underline{\underline{S}} - \underline{\underline{b}} \|}, \gamma > 0, & \text{plastic flow,} \\ \| \underline{\underline{S}} - \underline{\underline{b}} \| = (\sigma_y - \lambda \Sigma_H) / s, & \text{yield limit,} \\ \left(\underline{\underline{S}} - \underline{\underline{b}} \right) : \left(\dot{\underline{\underline{S}}} - \dot{\underline{\underline{b}}} \right) = 0, & \text{yield limit time invariance,} \\ \dot{\underline{\underline{b}}} = \frac{kE}{E - k} \dot{\underline{\underline{\varepsilon}}}^p, & \text{kinematic hardening rule,} \\ \dot{\underline{\underline{S}}} = dev\dot{\underline{\underline{\Sigma}}} - \frac{E}{1 + \nu} \dot{\underline{\underline{\varepsilon}}}^p, & \text{localisation rule.} \end{array} \right. \quad (19)$$

$$\left\{ \begin{array}{ll} \dot{\underline{\underline{\varepsilon}}}^p = \gamma \frac{\underline{\underline{S}} - \underline{\underline{b}}}{\| \underline{\underline{S}} - \underline{\underline{b}} \|}, \gamma > 0, & \text{plastic flow,} \\ \| \underline{\underline{S}} - \underline{\underline{b}} \| = (\sigma_y - \lambda \Sigma_H) / s, & \text{yield limit,} \\ \left(\underline{\underline{S}} - \underline{\underline{b}} \right) : \left(\dot{\underline{\underline{S}}} - \dot{\underline{\underline{b}}} \right) = 0, & \text{yield limit time invariance,} \\ \dot{\underline{\underline{b}}} = \frac{kE}{E - k} \dot{\underline{\underline{\varepsilon}}}^p, & \text{kinematic hardening rule,} \\ \dot{\underline{\underline{S}}} = dev\dot{\underline{\underline{\Sigma}}} - \frac{E}{1 + \nu} \dot{\underline{\underline{\varepsilon}}}^p, & \text{localisation rule.} \end{array} \right. \quad (20)$$

$$\left\{ \begin{array}{ll} \dot{\underline{\underline{\varepsilon}}}^p = \gamma \frac{\underline{\underline{S}} - \underline{\underline{b}}}{\| \underline{\underline{S}} - \underline{\underline{b}} \|}, \gamma > 0, & \text{plastic flow,} \\ \| \underline{\underline{S}} - \underline{\underline{b}} \| = (\sigma_y - \lambda \Sigma_H) / s, & \text{yield limit,} \\ \left(\underline{\underline{S}} - \underline{\underline{b}} \right) : \left(\dot{\underline{\underline{S}}} - \dot{\underline{\underline{b}}} \right) = 0, & \text{yield limit time invariance,} \\ \dot{\underline{\underline{b}}} = \frac{kE}{E - k} \dot{\underline{\underline{\varepsilon}}}^p, & \text{kinematic hardening rule,} \\ \dot{\underline{\underline{S}}} = dev\dot{\underline{\underline{\Sigma}}} - \frac{E}{1 + \nu} \dot{\underline{\underline{\varepsilon}}}^p, & \text{localisation rule.} \end{array} \right. \quad (21)$$

$$\left\{ \begin{array}{ll} \dot{\underline{\underline{\varepsilon}}}^p = \gamma \frac{\underline{\underline{S}} - \underline{\underline{b}}}{\| \underline{\underline{S}} - \underline{\underline{b}} \|}, \gamma > 0, & \text{plastic flow,} \\ \| \underline{\underline{S}} - \underline{\underline{b}} \| = (\sigma_y - \lambda \Sigma_H) / s, & \text{yield limit,} \\ \left(\underline{\underline{S}} - \underline{\underline{b}} \right) : \left(\dot{\underline{\underline{S}}} - \dot{\underline{\underline{b}}} \right) = 0, & \text{yield limit time invariance,} \\ \dot{\underline{\underline{b}}} = \frac{kE}{E - k} \dot{\underline{\underline{\varepsilon}}}^p, & \text{kinematic hardening rule,} \\ \dot{\underline{\underline{S}}} = dev\dot{\underline{\underline{\Sigma}}} - \frac{E}{1 + \nu} \dot{\underline{\underline{\varepsilon}}}^p, & \text{localisation rule.} \end{array} \right. \quad (22)$$

In all cases, we get (see annex 'Multi-dimensional analysis')

$$\left(\underline{\underline{S}} - \underline{\underline{b}} \right) (s, t + dt) = \frac{\left(\underline{\underline{S}} - \underline{\underline{b}} \right)_{trial} (s, t + dt)}{1 + \eta}, \quad (23)$$

with

$$\eta = \max \left\{ \underbrace{0}_{\text{elastic regime}}, \underbrace{\frac{\| \underline{\underline{S}} - \underline{\underline{b}} \|_{trial}}{(\sigma_y - \lambda \Sigma_H) / s} - 1}_{\substack{\text{plastic regime when this number is positive}}} \right\},$$

$$\left(\underline{\underline{S}} - \underline{\underline{b}}\right)_{trial}(s, t + dt) = \left(\underline{\underline{S}} - \underline{\underline{b}}\right)(s, t) + dev \dot{\underline{\underline{\Sigma}}}(t) dt.$$

That is to say, when the structure is in elastic regime at time t and scale s , we have $\left(\underline{\underline{S}} - \underline{\underline{b}}\right)(s, t) = \left(\underline{\underline{S}} - \underline{\underline{b}}\right)_{trial}(s, t)$. Otherwise, if the norm of $\left(\underline{\underline{S}} - \underline{\underline{b}}\right)_{trial}(s, t)$ is greater than the local yield limit $(\sigma_y - \lambda \Sigma_H) / s$, $\left(\underline{\underline{S}} - \underline{\underline{b}}\right)(s, t)$ will be projected on the yield limit.

Knowing the distinction between elastic and plastic regime under multiple scales, we compute the general expression of the dissipated energy rate.

$$\dot{w}(s) = \left(\underline{\underline{S}} - \underline{\underline{b}}\right) : \dot{\underline{\underline{\epsilon}}}^p = \gamma \frac{\sigma_y - \lambda \Sigma_H}{s}. \quad (24)$$

From Eq.(A.5) and Eq.(A.8) in annex, we get:

$$E\gamma dt = \left\langle \left\| \underline{\underline{S}} - \underline{\underline{b}} \right\|_{trial} - \frac{\sigma_y - \lambda \Sigma_H}{s} \right\rangle / \left(\frac{1}{1 + \nu} + \frac{k}{E - k} \right) = \left\langle \left\| \underline{\underline{S}} - \underline{\underline{b}} \right\|_{trial} - \frac{\sigma_y - \lambda \Sigma_H}{s} \right\rangle \frac{(E - k)(1 + \nu)}{(E + k\nu)}, \quad (25)$$

where $\langle \rangle$ is Macaulay bracket symbol defined as $\langle m \rangle = 0$ if $m \leq 0$, otherwise $\langle m \rangle = m$.

We replace γ deduced from Eq.(25) in Eq.(24) to give the expression of local energy dissipation rate at scale s :

$$\dot{w}(s) dt = \frac{(E - k)(1 + \nu)}{E(E + k\nu)} \left\langle \left\| \underline{\underline{S}} - \underline{\underline{b}} \right\|_{trial} - \frac{\sigma_y - \lambda \Sigma_H}{s} \right\rangle \frac{\sigma_y - \lambda \Sigma_H}{s}. \quad (26)$$

With Eq.(15), the final expression of energy dissipation W during time step dt writes:

$$\begin{aligned} W &= \dot{W} dt \\ &= \frac{1}{2} \sum_i \omega_i \dot{w} \left[\left(\frac{x_i + 1}{2} \right)^{\frac{1}{1-\beta}} \right] dt \\ &= \frac{(E - k)(1 + \nu)}{2E(E + k\nu)} \sum_i \omega_i \left\langle \left\| \underline{\underline{S}} - \underline{\underline{b}} \right\|_{trial} - \frac{\sigma_y - \lambda \Sigma_H}{\left(\frac{x_i + 1}{2} \right)^{\frac{1}{1-\beta}}} \right\rangle \frac{\sigma_y - \lambda \Sigma_H}{\left(\frac{x_i + 1}{2} \right)^{\frac{1}{1-\beta}}}. \end{aligned} \quad (27)$$

We have the damage accumulation deduced in Eq.(16):

$$g_{n+1} = g_n + \frac{\dot{W} dt}{W_F} = g_n + \frac{W}{W_F},$$

$$\text{with } D_n = \left[1 - \left(1 - g_n^{\frac{1}{1-\alpha}} \right)^{\frac{1}{\gamma+1}} \right].$$

Now we are able to put these formula into numerical tests.

5 Test on different load histories

5.1. One dimensional application to simple cyclic data

The test is first performed on a sinusoidal axial load $\Sigma = C \sin(t)$ with parameters in Table 1, giving a deviatoric amplitude $S_{max} = \sqrt{\frac{2}{3}}C$.

Parameters	Value
Load	$\Sigma = 5e8 \sin(t)$ Pa
Young's modulus	$E = 2e11$ Pa
Hardening parameter	$k = 6e8$ Pa
Weakening scales distribution exponent	$\beta = 3$
Hydrostatic pressure sensitivity	$\lambda = 0.5$
Macroscopic yield stress	$\sigma_y = 6.38e8$ Pa
Material parameter from Chaboche law(Wohler curve exponent)	$\gamma = 0.5$
Non-linearity of damage accumulation	$\alpha = 0.5$
Initial damage	$D = 0$
Initial time	$t = 0$ s
Dissipated energy to failure per unit volume	$W_F = 3e6$ J
Looping step	1e-4 s

Table 1: Material parameters in a simple cyclic load

We use matlab to realize our analytical method. We plot $\|S - b\|_{trial}$ and $\|S - b\|$ for two different scales ($s_1 = 21.21657929229650$ and $s_8 = 2.176132808422946$) in Figure 3.

The nonlinearity is determined by

$$\alpha = 1 - a \left\langle \frac{\max_t \sqrt{J_{2,a}(t)} + a_c P_{max}(t) - b_c}{\sigma_u - 2 \max \sqrt{J_{2,a}}} \right\rangle,$$

which is predominated by a certain fatigue criterion, for simplicity we take α as a constant. The damage evolves like in Figure 4, where we compare the damage evolution as predicted by the cycle accumulation Eq.(7) and by the numerical strategy of section 4.

Now we compare the result to the one demonstrated in Figure 2. The first cycle has 3 phases which have the energy loss identical to phase 1. The following cycles each have 4 times energy loss as phase 1. We can see from Figure 5 and Figure 6 the difference between cyclic load calculation and numerical method as function of time (time step=1/5000s and 1/15000s separately). Because the step by step damage accumulation grows in a power law, so the amplitude of difference grows with time. However, the difference between the two

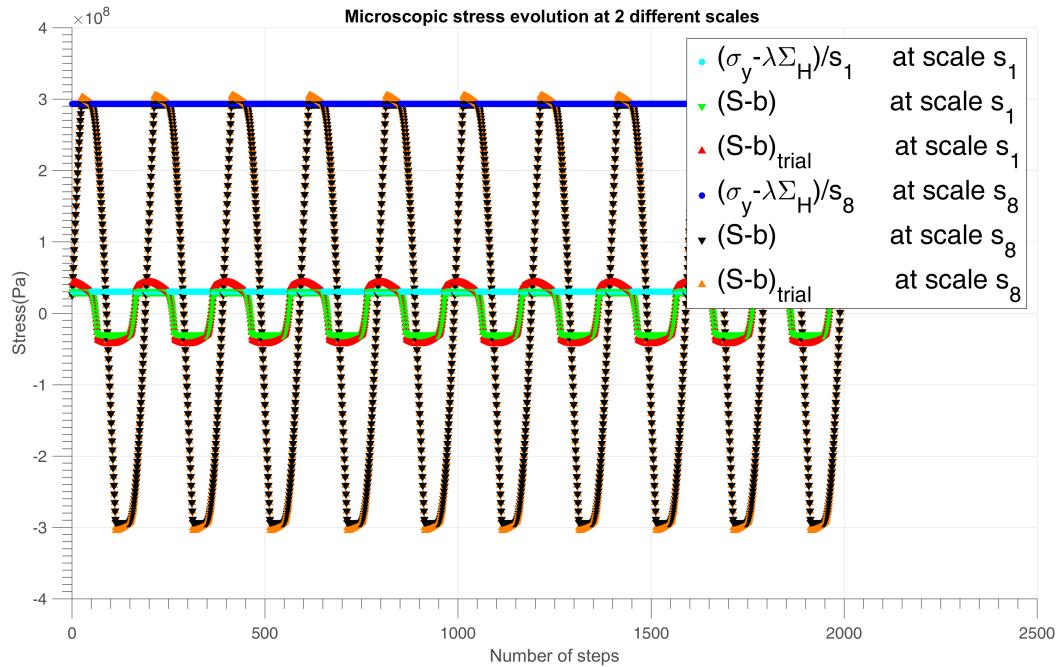


Figure 3: Microscopic $(\underline{S} - \underline{b})_{trial}$ and $(\underline{S} - \underline{b})$ evolution with time under different weakening scales in sinusoidal load

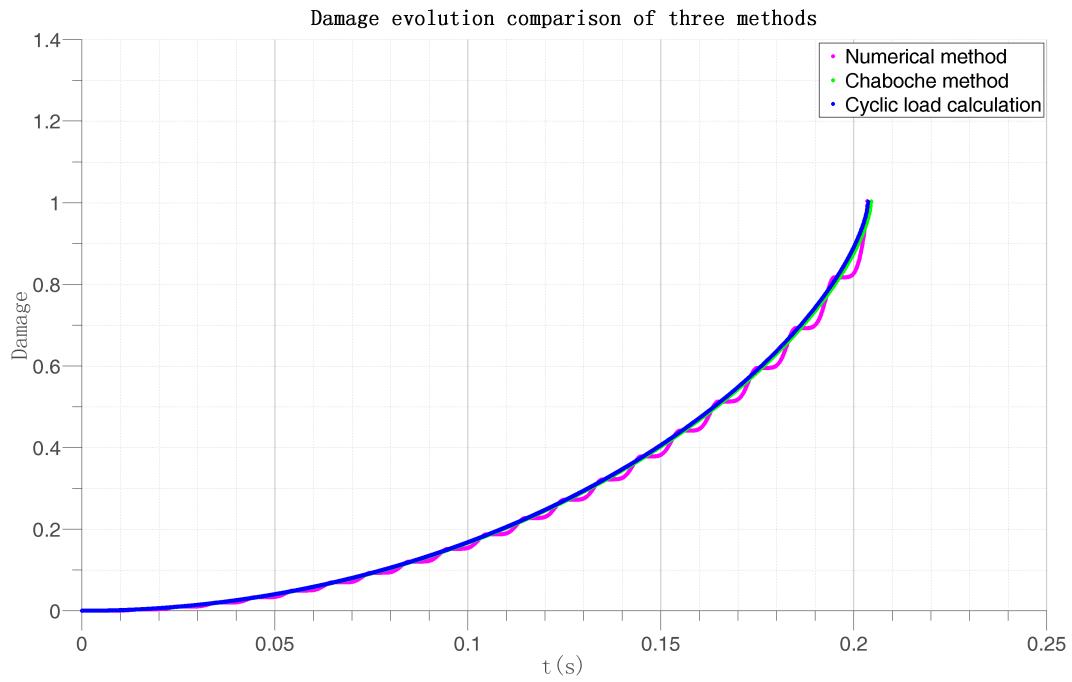


Figure 4: Damage evolution with time under sinusoidal load with two different methods

methods swing around 0 and from Figure 4 we can see the difference is not symmetrical, we could consider the numerical method converges in cyclic load calculation method.

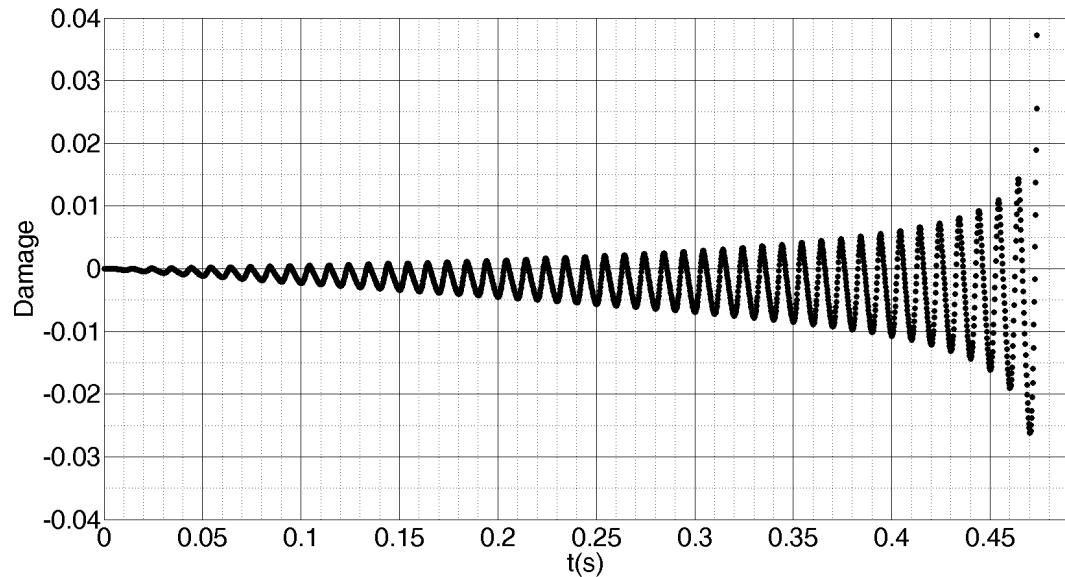


Figure 5: Difference between cyclic load calculation and numerical method as function of time (time step=1/5000s)

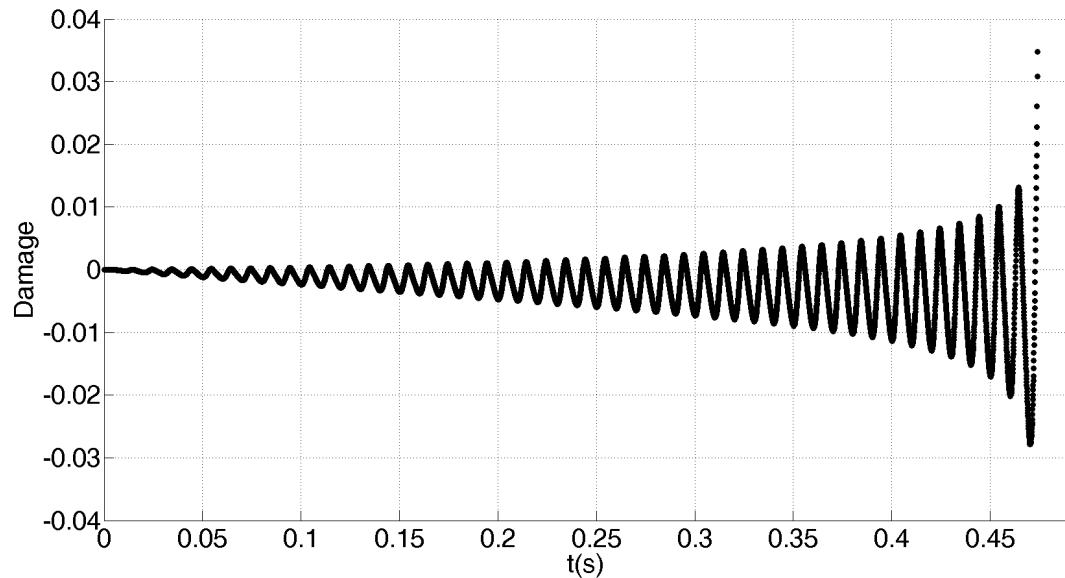


Figure 6: Difference between cyclic load calculation and numerical method as function of time (time step=1/15000s)

The cyclic load calculation is only valid for very simple such as proportional loading in fatigue, nevertheless it can still be used as a comparison group to verify the numerical results. The outcome seems

satisfactory. Hence, to be more general for any loading history, we adopt the numerical method.

5.2. One dimensional application to PSA data

In this test, we reconstruct a unidimensional macroscopic stress history from recorded force data proposed by PSA group.

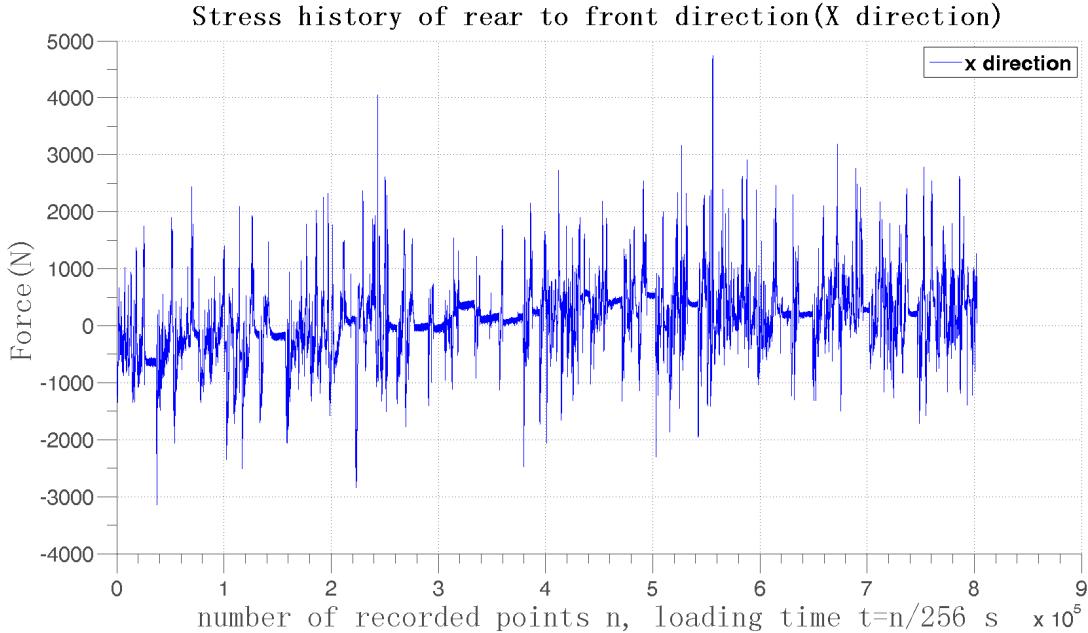


Figure 7: Loading history of X direction, force vs the record index n , with 256 sample recorded per second

The sample recording rate is 256 per second. In order to accumulate damage using very small steps, we have created 10 additional points between every 2 recorded points by linear interpolation. So the sample rate is $256 * 10$ per second.

The force on wheel is firstly considered as under uniaxial loading F_x . Here we temporally set $\Sigma_x = F_x/A$ where $A = \frac{1}{1e6} m^2$ is the area of force, and $W_F = 3e6 J$. The other data are as Table 1. The plot of $\|\underline{\underline{S}} - \underline{\underline{b}}\|_{trial}$ and $\|\underline{\underline{S}} - \underline{\underline{b}}\|$ under 2 different scales ($s_1 = 21.21657929229650$ and $s_8 = 2.176132808422946$) are shown in Figure 8. The damage evolves like Figure 10.

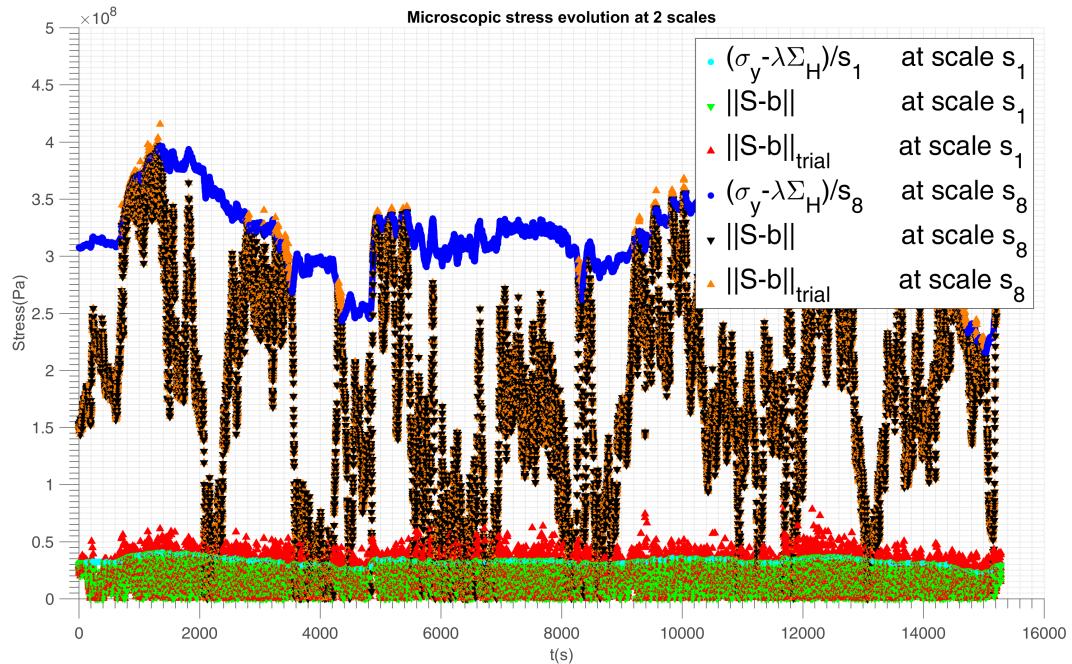


Figure 8: $\|S - b\|_{trial}$ and $\|S - b\|$ evolution with time under different weakening scales in PSA load history

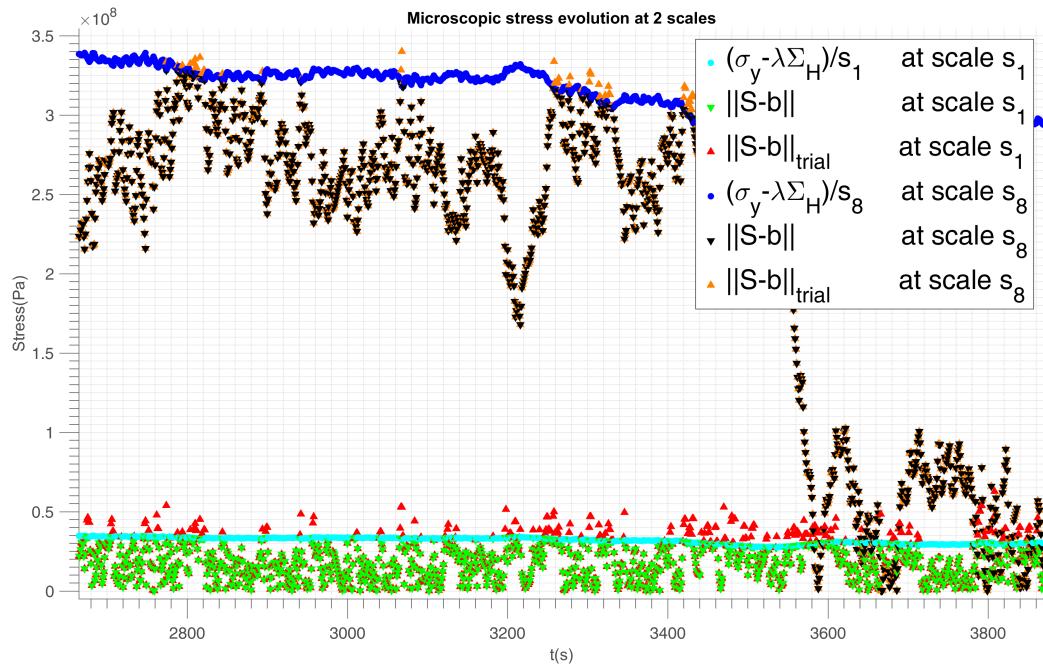


Figure 9: Circled area magnification in Figure 8 where there is more $\|S - b\|_{trial} > \sigma_y$ (plasticity) at s_1 than at s_8

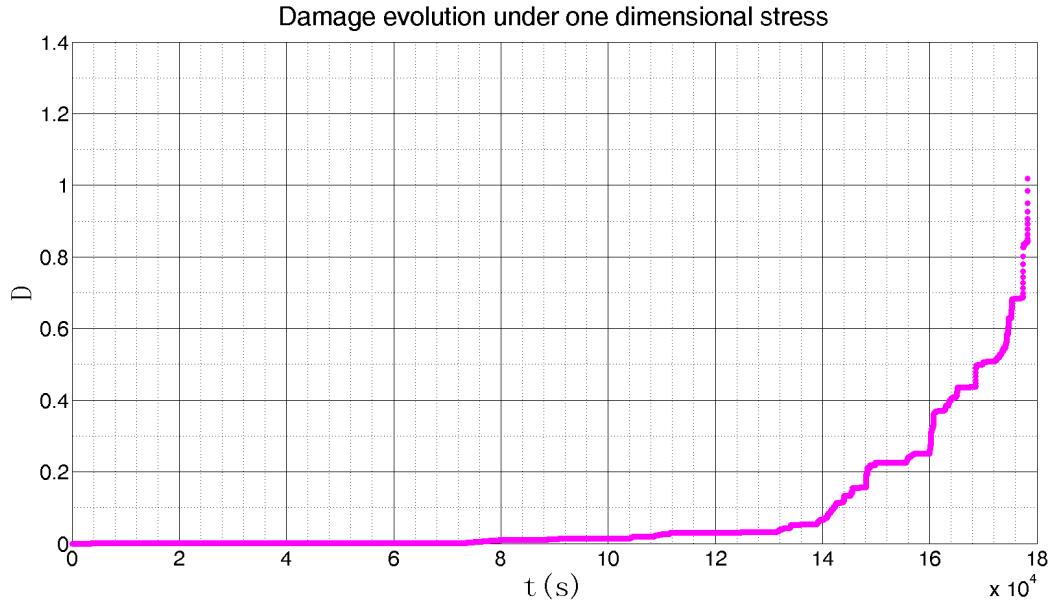


Figure 10: Damage evolution with time at one dimension PSA load history

5.3. Multi-dimensional application to PSA data

We now consider a situation where we have force recorded measured in 3 different directions as shown in Figure 11. In real case, the vertical force F_z is much larger than the axial and horizontal forces F_x and F_y ,

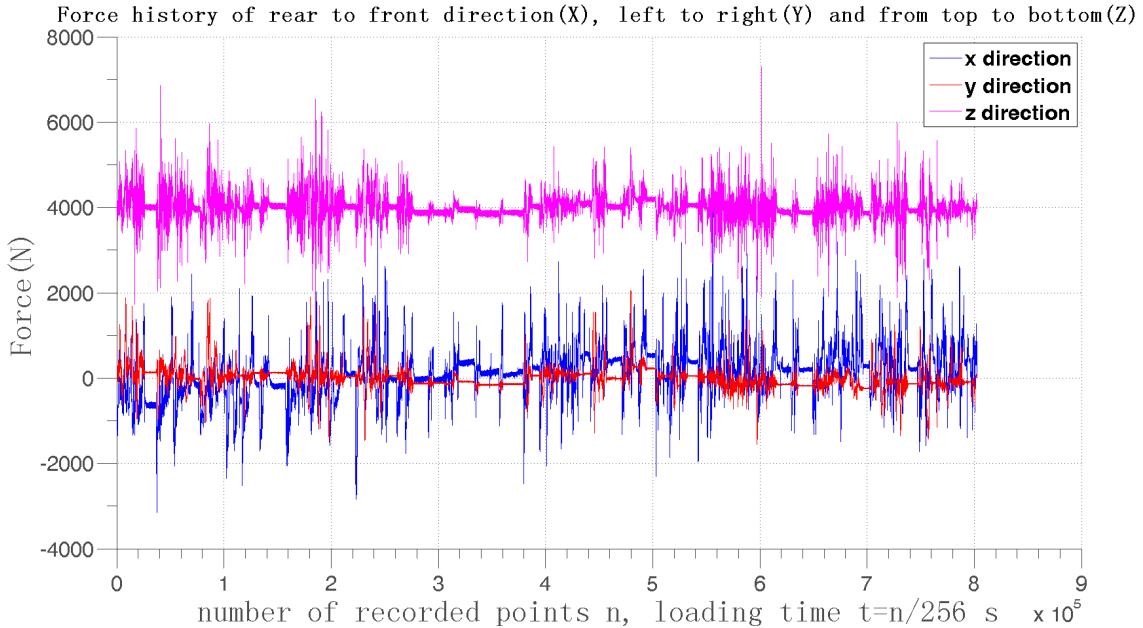


Figure 11: Loading history of 3 different directions

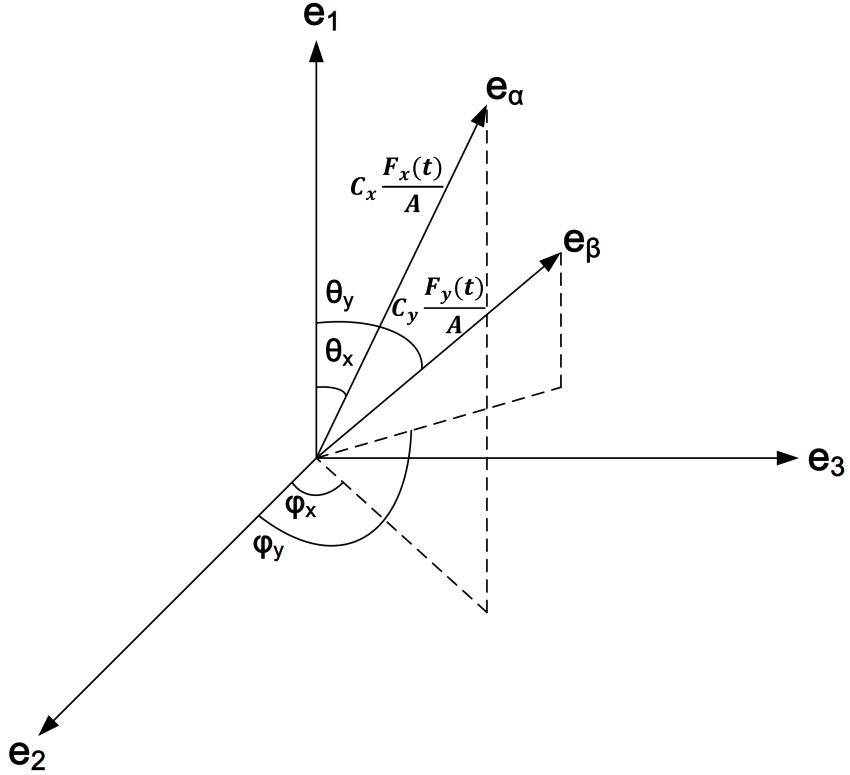


Figure 12: Loading in 3 different directions

as shown in Figure 11. However, in order to investigate large domains of interest, we first scale the axial and horizontal forces to reach comparable impact and transform them in principal stresses $c_x \frac{F_x}{A}$ applied along the stress principle vector \underline{e}_α (respectively \underline{e}_β) that we choose randomly (Figure 12). We therefore consider the following macroscopic stress tensor:

$$\underline{\underline{\Sigma}} = \frac{F_z(t)}{A} \underline{e}_1 \otimes \underline{e}_1 + c_x \frac{F_x(t)}{A} \underline{e}_\alpha \otimes \underline{e}_\alpha + c_y \frac{F_y(t)}{A} \underline{e}_\beta \otimes \underline{e}_\beta \quad (28)$$

where \underline{e}_α and \underline{e}_β are principal vectors whose spherical coordinate are θ_x , φ_x , θ_y and φ_y respectively:

$$\underline{e}_\alpha = \cos\theta_x \underline{e}_1 + \sin\theta_x \cos\varphi_x \underline{e}_2 + \sin\theta_x \sin\varphi_x \underline{e}_3,$$

$$\underline{e}_\beta = \cos\theta_y \underline{e}_1 + \sin\theta_y \cos\varphi_y \underline{e}_2 + \sin\theta_y \sin\varphi_y \underline{e}_3.$$

Here $F_x(t)$, $F_y(t)$, $F_z(t)$ are from test data, and θ_x , φ_x , θ_y , φ_y are structural parameters to be chosen randomly. The physical data are the same with parameters in Table 1. The structural data we choose is shown in Table 2.

The underlying assumption is that a unit load on wheel in direction \underline{e}_x creates a stress tensor at point

Parameter	$A(m^2)$	c_x	c_y	θ_x	φ_x	θ_y	φ_y
Value	1/6e4	10	60	0.5	0.3	0.6	0.4

Table 2: The structural data in 3D analysis

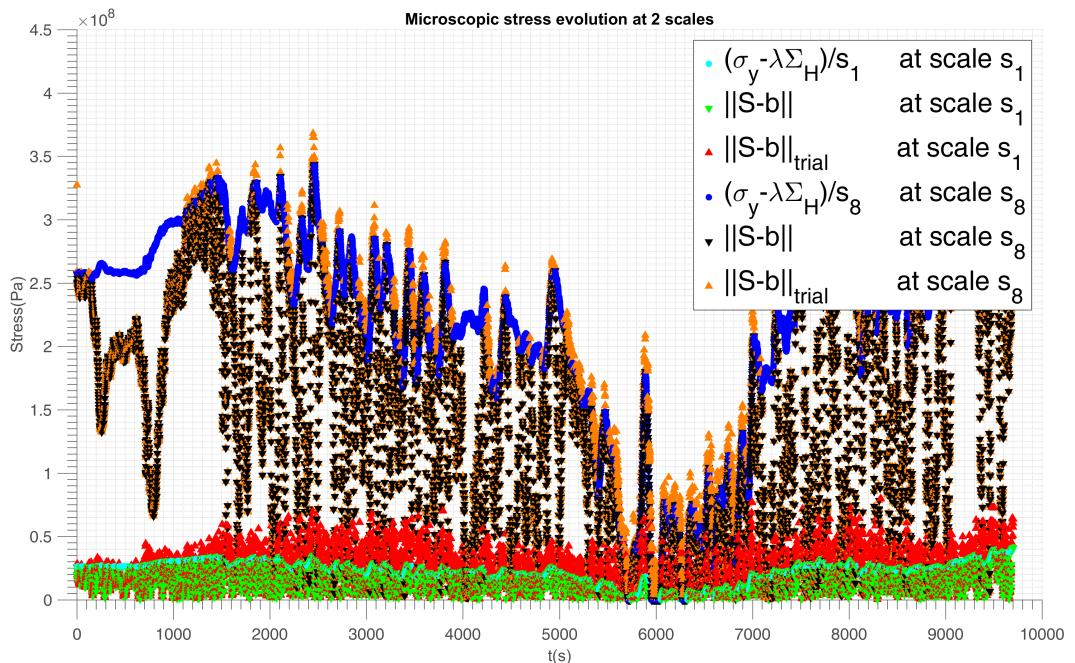
M given by:

$$c_x \frac{F_x(t)}{A} \underline{e}_\alpha \otimes \underline{e}_\alpha,$$

where $\underline{e}_\alpha \otimes \underline{e}_\alpha$ defines the local structural response of the vehicle.

Replacing \underline{e}_α and \underline{e}_β in Eq.(28) we get the stress tensor in Eq.(A.9) in the annex.

The plot of $\|\underline{S} - \underline{b}\|_{trial}$ and $\|\underline{S} - \underline{b}\|$ under 2 different scales are shown in Figure 13.

Figure 13: $\|\underline{S} - \underline{b}\|_{trial}$ and $\|\underline{S} - \underline{b}\|$ evolution with time under different weakening scales in PSA load history

In the load history, when $\|\underline{S} - \underline{b}\|_{trial} > \sigma_y$, the damage accumulates. However, under scale s_8 , there are much less damage accumulation than under scale s_1 . In this way we do not neglect the small influences in load history and the big fluctuation in stress is magnified which reflects the real situation.

The damage evolves like in Figure 14.

We can improve the result by inserting more arithmetic sequence points between every 2 recorded points. As is shown in Table.3 :

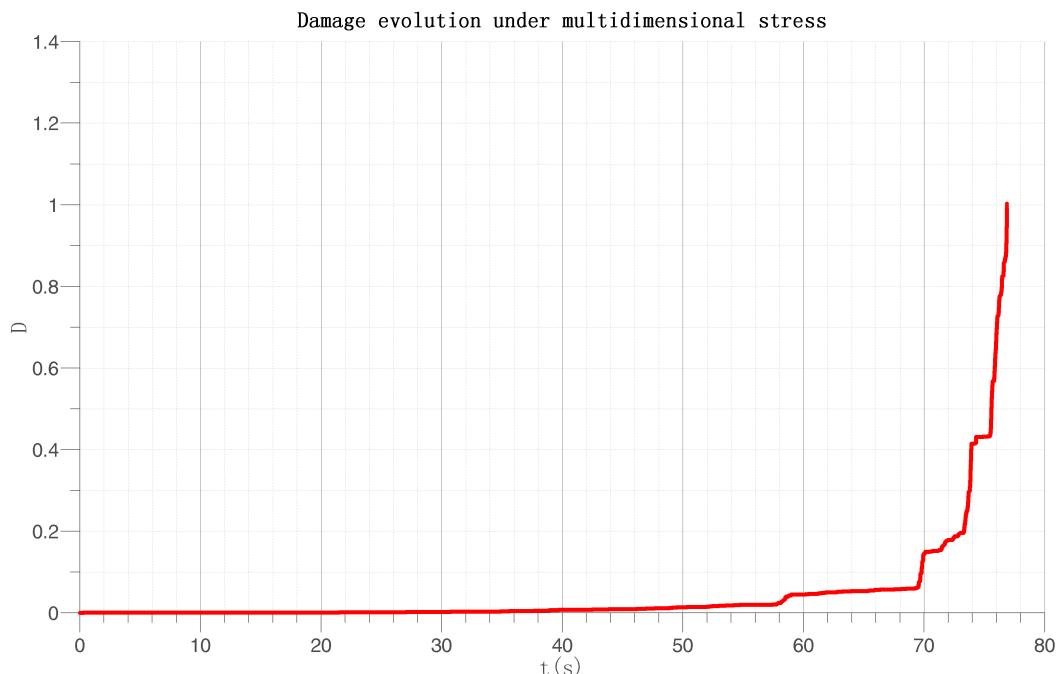


Figure 14: Damage evolution under multidimensional stress

Table 3: Arithmetic sequence points density effect

Arithmetic sequence points between every two points	Total time to failure(s)
10	78.63711
20	72.24630
30	70.25793
50	68.69148
100	67.49223

6 Discussion

We work on the stress tensor directly in 3D analysis in stead of using the multidimensional equivalent stress. The strategy can be made more complex by introducing a local space averaging process in the calculation of the local damage, and by taking more general plastic flows. The energy based fatigue approach takes into account impurities and hardness in the material and is applicable to any type of micro plasticity law and multiaxial load geometry. The small step-by-step strategy does not ignore small fluctuations in the load history.

Further research of energy based failure criteria should be focused on the following aspects:

1. The accommodation law might be more elaborate than kinematic hardening.
2. The differentiation of shear stress and normal stress effect on fatigue life should be clarified.
3. The non-linearity parameter α contains the stress σ , so it can evolve with time. But for complex loading history, should it change at every time step?

Acknowledgments

We are grateful for the financial and technical support of Chaire PSA.

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Appendices

Appendix A DETAILED EXPLOITATION

A DETAILED DESCRIPTION OF ANALYTICAL EXPLOITATION ON UNIAXIAL CYCLE

Phase 1: The deviatoric stress amplitude increases from σ_y/s to S_{max} .

The material is in local plastic regime, then $\dot{\varepsilon}^p > 0$ and $\dot{\sigma} - \dot{b} = 0 \Rightarrow \dot{\Sigma} - \frac{E}{1+\nu} \dot{\varepsilon}^p = \frac{kE}{E-k} \dot{\varepsilon}^p \Rightarrow$

$$\dot{\varepsilon}^p = \frac{(E-k)(1+\nu)}{E(E+k\nu)} \dot{\Sigma}.$$

$\Rightarrow \dot{\varepsilon}^p$ varies from 0 to $\frac{(E-k)(1+\nu)(S_{max} - \sigma_y/s)}{E(E+k\nu)}$.

From Taylor-Lin scale transition model:

$$\dot{\sigma} = \dot{\Sigma} - \frac{E}{1+\nu} \dot{\varepsilon}_p = \dot{\Sigma} - \frac{E-k}{E-\nu k} \dot{\Sigma} = \frac{k(1-\nu)}{E-k\nu} \dot{\Sigma}.$$

$\Rightarrow \sigma$ varies from σ_y/s to $\sigma_y/s + \frac{k(1-\nu)(S_{max} - \sigma_y/s)}{E-k\nu}$.

$$\dot{b} = \dot{\Sigma} - \frac{E}{1+\nu} \dot{\varepsilon}_p = \dot{\Sigma} - \frac{E-k}{E-\nu k} \dot{\Sigma} = \frac{k(1-\nu)}{E-k\nu} \dot{\Sigma}.$$

$\Rightarrow b$ varies from 0 to $\frac{k(1-\nu)(S_{max} - \sigma_y/s)}{E-k\nu}$.

So the energy dissipation rate is:

$$(\sigma - b) \dot{\varepsilon}^p = \frac{\sigma_y}{s} \dot{\varepsilon}^p = \frac{\sigma_y}{s} \frac{(E-k)(1+\nu)}{E(E+k\nu)} \dot{\Sigma}.$$

The energy dissipation is:

$$(\sigma - b) \Delta \varepsilon^p = \frac{\sigma_y}{s} \frac{(E-k)(1+\nu)(S_{max} - \sigma_y/s)}{E(E+k\nu)}.$$

Phase 2: The deviatoric stress amplitude decreases from S_{max} to $S_{max} - 2\sigma_y/s$.

The material is in local elastic regime, then $\dot{\varepsilon}^p = 0$ and $\dot{\sigma} - \dot{b} = 0 \Rightarrow$

$$\dot{b} = 0, \dot{\sigma} = \dot{\Sigma} - \frac{E}{1+\nu} \dot{\varepsilon}_p = \dot{\Sigma}.$$

σ varies from $\sigma_y/s + \frac{k(1-\nu)(S_{max} - \sigma_y/s)}{E-k\nu}$ to $-\sigma_y/s + \frac{k(1-\nu)(S_{max} - \sigma_y/s)}{E-k\nu}$.

$\sigma - b$ varies from σ_y/s to $-\sigma_y/s$.

The energy dissipation rate is:

$$(\sigma - b)\dot{\varepsilon}^p = 0.$$

Phase 3: The deviatoric stress amplitude decreases from $S_{max} - 2\sigma_y/s$ to $-S_{max}$.

The material is in local plastic regime, then $\dot{\varepsilon}^p > 0$ and $\dot{\sigma} - \dot{b} = 0 \Rightarrow$

$$\dot{\varepsilon}^p = \frac{(E - k)(1 + \nu)}{E(E + k\nu)} \dot{\Sigma}$$

as opposite to phase 1 for $\dot{\Sigma} < 0$.

$$\Rightarrow \dot{\varepsilon}^p \text{ varies from } \frac{(E - k)(1 + \nu)(S_{max} - \sigma_y/s)}{E(E + k\nu)} \text{ to } \frac{(E - k)(1 + \nu)(S_{max} - \sigma_y/s - S_{max} - (S_{max} - 2\sigma_y/s))}{E(E + k\nu)} = -\frac{(E - k)(1 + \nu)(S_{max} - \sigma_y/s)}{E(E + k\nu)}.$$

From Taylor-Lin scale transition model:

$$\dot{\sigma} = \dot{\Sigma} - \frac{E}{1 + \nu} \dot{\varepsilon}_p = \dot{\Sigma} - \frac{E - k}{E - \nu k} \dot{\Sigma} = \frac{k(1 - \nu)}{E - \nu k} \dot{\Sigma}.$$

$$\Rightarrow \sigma \text{ varies from } -\sigma_y/s + \frac{k(1 - \nu)(S_{max} - \sigma_y/s)}{E - \nu k} \text{ to } -\sigma_y/s - \frac{k(1 - \nu)(S_{max} - \sigma_y/s)}{E - \nu k}.$$

$$\dot{b} = \dot{\Sigma} - \frac{E}{1 + \nu} \dot{\varepsilon}_p = \dot{\Sigma} - \frac{E - k}{E - \nu k} \dot{\Sigma} = \frac{k(1 - \nu)}{E - \nu k} \dot{\Sigma}.$$

$$\Rightarrow b \text{ varies from } \frac{k(1 - \nu)(S_{max} - \sigma_y/s)}{E - \nu k} \text{ to } -\frac{k(1 - \nu)(S_{max} - \sigma_y/s)}{E - \nu k}.$$

So the energy dissipation rate is:

$$(\sigma - b)\dot{\varepsilon}^p = -\frac{\sigma_y}{s} \dot{\varepsilon}^p = -\frac{\sigma_y}{s} \frac{(E - k)(1 + \nu)}{E(E + k\nu)} \dot{\Sigma}.$$

The energy dissipation is:

$$(\sigma - b)\Delta\varepsilon^p = -\frac{\sigma_y}{s} \frac{(E - k)(1 + \nu)(-2S_{max} + 2\sigma_y/s)}{E(E + k\nu)} = \frac{2\sigma_y}{s} \frac{(E - k)(1 + \nu)(S_{max} - \sigma_y/s)}{E(E + k\nu)}.$$

Phase 4: The deviatoric stress amplitude increases from $-S_{max}$ to $-S_{max} + 2\sigma_y/s$.

The material is in local elastic regime, then $\dot{\varepsilon}^p = 0$ and $\dot{\sigma} - \dot{b} = 0 \Rightarrow$

$$\dot{b} = 0, \dot{\sigma} = \dot{\Sigma} - \frac{E}{1 + \nu} \dot{\varepsilon}_p = \dot{\Sigma}.$$

$$\sigma \text{ varies from } -\sigma_y/s - \frac{k(1 - \nu)(S_{max} - \sigma_y/s)}{E - \nu k} \text{ to } \sigma_y/s - \frac{k(1 - \nu)(S_{max} - \sigma_y/s)}{E - \nu k}.$$

$\sigma - b$ varies from $-\sigma_y/s$ to σ_y/s .

So the energy dissipation rate is:

$$(\sigma - b)\dot{\varepsilon}^p = 0.$$

Phase 5: The deviatoric stress amplitude increases from $-S_{max} + 2\sigma_y/s$ to σ_y/s .

The material is in local plastic regime, then $\dot{\varepsilon}^p > 0$ and $\dot{\sigma} - \dot{b} = 0 \Rightarrow$

$$\dot{\varepsilon}^p = \frac{(E - k)(1 + \nu)}{E(E + k\nu)} \dot{\Sigma}$$

as in phase 1.

$$\Rightarrow \dot{\varepsilon}^p \text{ varies from } -\frac{(E - k)(1 + \nu)(S_{max} - \sigma_y/s)}{E(E + k\nu)} \text{ to } 0.$$

$$\dot{\sigma} = \dot{\Sigma} - \frac{E}{1 + \nu} \dot{\varepsilon}_p = \dot{\Sigma} - \frac{E - k}{E - \nu k} \dot{\Sigma} = \frac{k(1 - \nu)}{E - k\nu} \dot{\Sigma}.$$

$$\Rightarrow \sigma \text{ varies from } \sigma_y/s - \frac{k(1 - \nu)(S_{max} - \sigma_y/s)}{E - k\nu} \text{ to } \sigma_y/s.$$

$$\dot{b} = \dot{\Sigma} - \frac{E}{1 + \nu} \dot{\varepsilon}_p = \dot{\Sigma} - \frac{E - k}{E - \nu k} \dot{\Sigma} = \frac{k(1 - \nu)}{E - k\nu} \dot{\Sigma}.$$

$$\Rightarrow b \text{ varies from } -\frac{k(1 - \nu)(S_{max} - \sigma_y/s)}{E - k\nu} \text{ to } 0.$$

So the energy dissipation rate is:

$$(\sigma - b) \dot{\varepsilon}^p = \frac{\sigma_y}{s} \dot{\varepsilon}^p = \frac{\sigma_y}{s} \frac{(E - k)(1 + \nu)}{E(E + k\nu)} \dot{\Sigma}.$$

The energy dissipation is:

$$(\sigma - b) \Delta \varepsilon^p = \frac{\sigma_y}{s} \frac{(E - k)(1 + \nu)(S_{max} - \sigma_y/s)}{E(E + k\nu)}.$$

From the three phase analysis in local plastic regime, the dissipated energy is like $dW(\text{phase1}) = \frac{1}{2} dW(\text{phase3}) = dW(\text{phase5})$ and the dissipation rate is like $d\dot{W}(\text{phase1}) = d\dot{W}(\text{phase3}) = d\dot{W}(\text{phase5})$.

$$d\dot{W} = \frac{(E - k)(1 + \nu)}{E(E - k\nu)} \left(\frac{\sigma_y}{s} \right) |\dot{\Sigma}| \quad (\text{A.1})$$

MULTI-DIMENSIONAL PLASTIC AND ELASTIC REGIME ANALYSIS

At a certain scale s_i , after elimination of $\underline{\dot{\epsilon}}^p$, there are

$$\underline{\dot{S}} - \underline{\dot{b}} = dev \underline{\dot{\Sigma}} - E\gamma \left(\frac{1}{1+\nu} + \frac{k}{E-k} \right) \frac{\underline{S} - \underline{b}}{\|\underline{S} - \underline{b}\|}.$$

If we are at yield limit at $(t+dt)$, we get on the other hand:

$$\begin{aligned} \left(\underline{S} - \underline{b} \right) (t+dt) &= \left(\underline{S} - \underline{b} \right) (t) + \left(\dot{\underline{S}} - \dot{\underline{b}} \right) dt, \\ \left\| \left(\underline{S} - \underline{b} \right) (t+dt) \right\| &= (\sigma_y - \lambda\sigma_m) / s_i. \end{aligned} \quad (\text{A.2})$$

Replacing $\left(\dot{\underline{S}} - \dot{\underline{b}} \right)$ in the integration by its expression we get:

$$\left(\underline{S} - \underline{b} \right) (t+dt) = \left(\underline{S} - \underline{b} \right) (t) + dev \underline{\dot{\Sigma}} dt - E\gamma dt \left(\frac{1}{1+\nu} + \frac{k}{E-k} \right) \frac{\left(\underline{S} - \underline{b} \right) (t+dt)}{\|\underline{S} - \underline{b}\| (t+dt)} \quad (\text{A.3})$$

Putting all terms with $\left(\underline{S} - \underline{b} \right) (t+dt)$ on the left hand side, we get:

$$\left(\underline{S} - \underline{b} \right) (t+dt) (1+\eta) = \left(\underline{S} - \underline{b} \right) (t) + dev \underline{\dot{\Sigma}} dt = \left(\underline{S} - \underline{b} \right)_{trial} (t+dt) \quad (\text{A.4})$$

with

$$\eta = \frac{E\gamma dt}{\|\underline{S} - \underline{b}\| (t+dt)} \left(\frac{1}{1+\nu} + \frac{k}{E-k} \right). \quad (\text{A.5})$$

To see whether the structure is in elastic or plastic regime at each time step, we use $\left(\underline{S} - \underline{b} \right)_{trial} (t+dt)$ to compare with the yield stress at the same scale s_i , thus to give a value to $\left(\underline{S} - \underline{b} \right) (t+dt)$.

Since $\left(\underline{S} - \underline{b} \right) (t+dt)$ is in the same direction as $\left(\underline{S} - \underline{b} \right)_{trial} (t+dt)$, we have

$$\left(\underline{S} - \underline{b} \right) (t+dt) = (\sigma_y - \lambda\sigma_m) / s \frac{\left(\underline{S} - \underline{b} \right)_{trial} (t+dt)}{\left\| \underline{S} - \underline{b} \right\|_{trial} (t+dt)} \quad (\text{A.6})$$

We now compare Eq.(A.4) and Eq.(A.6), the only solution is to have:

$$1 + \eta = \frac{\left\| \underline{S} - \underline{b} \right\|_{trial}}{(\sigma_y - \lambda\sigma_m) / s} \quad (\text{A.7})$$

that is:

$$\eta = \frac{\left\| \underline{S} - \underline{b} \right\|_{trial}}{(\sigma_y - \lambda\sigma_m) / s} - 1 \quad (\text{A.8})$$

which is positive in plastic regime.

3D STRESS TENSOR

$$\begin{aligned}
 \Sigma &= \frac{F_z}{A} \underline{e}_1 \otimes \underline{e}_1 + c_x \frac{F_x}{A} \underline{e}_\alpha \otimes \underline{e}_\alpha + c_y \frac{F_y}{A} \underline{e}_\beta \otimes \underline{e}_\beta \\
 &= \frac{F_z}{A} \underline{e}_1 \otimes \underline{e}_1 + c_x \frac{F_x}{A} (\cos\theta_x \underline{e}_1 + \sin\theta_x \cos\varphi_x \underline{e}_2 + \sin\theta_x \sin\varphi_x \underline{e}_3) \otimes (\cos\theta_x \underline{e}_1 + \sin\theta_x \cos\varphi_x \underline{e}_2 + \sin\theta_x \sin\varphi_x \underline{e}_3) \\
 &\quad + c_y \frac{F_y}{A} (\cos\theta_y \underline{e}_1 + \sin\theta_y \cos\varphi_y \underline{e}_2 + \sin\theta_y \sin\varphi_y \underline{e}_3) \otimes (\cos\theta_y \underline{e}_1 + \sin\theta_y \cos\varphi_y \underline{e}_2 + \sin\theta_y \sin\varphi_y \underline{e}_3) \\
 &= \left(\frac{F_z}{A} + c_x \frac{F_x}{A} \cos^2 \theta_x + c_y \frac{F_y}{A} \cos^2 \theta_y \right) \underline{e}_1 \otimes \underline{e}_1 \\
 &\quad + \left(c_x \frac{F_x}{A} \cos\theta_x \sin\theta_x \cos\varphi_x + c_y \frac{F_y}{A} \cos\theta_y \sin\theta_y \cos\varphi_y \right) (\underline{e}_1 \otimes \underline{e}_2 + \underline{e}_2 \otimes \underline{e}_1) \\
 &\quad + \left(c_x \frac{F_x}{A} \cos\theta_x \sin\theta_x \sin\varphi_x + c_y \frac{F_y}{A} \cos\theta_y \sin\theta_y \sin\varphi_y \right) (\underline{e}_1 \otimes \underline{e}_3 + \underline{e}_3 \otimes \underline{e}_1) \\
 &\quad + \left(c_x \frac{F_x}{A} \sin^2 \theta_x \cos^2 \varphi_x + c_y \frac{F_y}{A} \sin^2 \theta_y \cos^2 \varphi_y \right) \underline{e}_2 \otimes \underline{e}_2 \\
 &\quad + \left(c_x \frac{F_x}{A} \sin^2 \theta_x \cos\varphi_x \sin\varphi_x + c_y \frac{F_y}{A} \sin^2 \theta_y \cos\varphi_y \sin\varphi_y \right) (\underline{e}_2 \otimes \underline{e}_3 + \underline{e}_3 \otimes \underline{e}_2) \\
 &\quad + \left(c_x \frac{F_x}{A} \sin^2 \theta_x \sin^2 \varphi_x + c_y \frac{F_y}{A} \sin^2 \theta_y \sin^2 \varphi_y \right) \underline{e}_3 \otimes \underline{e}_3
 \end{aligned} \tag{A.9}$$

Appendix B MATLAB CODE LISTING

```

1 ****
2 *
3 * CODING OF DAMAGE AND STRESS EVOLUTION OF A SINUSOIDAL LOAD (3 METHODS)
4 *
5 ****
6 % Program to get the Gauss-Legendre Quadrature results (Vectorized)
7 clear;clc;
8
9 dbstop if error
10 format long e
11 [x]= [-0.99555697 -0.976663921 -0.942974571 -0.894991998 -0.833442629 -0.759259263
12 -0.673566368...
13 -0.57766293 -0.473002731 -0.361172306 -0.243866884 -0.122864693 0 0.122864693
14 0.243866884 0.361172306...
15 0.473002731 0.57766293 0.673566368 0.759259263 0.833442629 0.894991998 0.942974571
16 0.976663921...
17 0.99555697];
18 [ weight]=[0.011393799 0.026354987 0.040939157 0.054904696 0.068038334
19 0.0801407 0.091028262...
20 0.100535949 0.108519624 0.114858259 0.119455764 0.122242443
21 0.123176054 0.122242443 0.119455764...
22 0.114858259 0.108519624 0.100535949 0.091028262 0.0801407
23 0.068038334 0.054904696 0.040939157...
24 0.026354987 0.011393799];
25 % [x]=xlsread('Gauss-Legendre Quadrature','Sheet1','b1:z1');
26 % [weight]=xlsread('Gauss-Legendre Quadrature','Sheet1','b2:z2');
27
28 E=2e11; %Youngs modulus
29 k=6e8; %hardening parameter
30 b=3; %weakening scales distribution exponent
31 nu=0.3; %poisson's ratio
32 tt=2e8; %torsion fatigue limit
33 ff=2.5e8; %bending fatigue limit
34 ac=(tt-ff/sqrt(3))/(ff/3); %crossland criterial constant
35 bc=tt; %crossland criterial constant
36 sigu=8e8; %ultimite stress
37 gam=0.5; %material parameter from Chaboche law(Wohler curve exponent)

```

```

32 y=6.38e8; %macroscopic yield stress
33 WF=3e6; %dissipated energy to failure per unit volume
34 load=5e8; %cyclic load
35 loadtensor= [ load 0 0;0 0 0;0 0 0];
36 stepnumber=200; %devide one cycle in 200 parts
37 f=50; %frequency of load
38
39 %-----numerical method-----
40 alp=0.5;
41 D=0; %initial damage
42 n=1; %initial recording point
43 G = (1 - (1 - D).^(gam + 1)).^(1-alp);
44 %-----to get the the first Sb-----
45 stress11=load*sin(2*pi/stepnumber);
46 m=1/3*sum(stress11+0+0);
47 dev1=[stress11 0 0 ;0 0 0 ;0 0 0 ]-m*diag([1,1,1]);
48 dev11=dev1(1,1); dev12=dev1(1,2); dev13=dev1(1,3);
49 dev21=dev1(2,1); dev22=dev1(2,2); dev23=dev1(2,3);
50 dev31=dev1(3,1); dev32=dev1(3,2); dev33=dev1(3,3);
51 [ s]= ([x]/2+1/2).^(1/(1-b)); %1*25
52
53 trial11=dev11; trial12=dev12; trial13=dev13;
54 trial21=dev21; trial22=dev22; trial23=dev23;
55 trial31=dev31; trial32=dev32; trial33=dev33;
56
57 normtrial(1)=norm([ trial11 , trial12 , trial13; trial21 , trial22 , trial23; trial31 ,
58 trial32 , trial33 ], 'fro');
59 [ eta]=bsxfun(@minus,bsxfun(@times,normtrial(1)/y,s),1); %1*25
60 eta( eta<0)=0;
61
62 Sb11=bsxfun(@rdivide,trial11,bsxfun(@plus,[ eta],1));Sb12=bsxfun(@rdivide,trial12,
63 bsxfun(@plus,[ eta],1));Sb13=bsxfun(@rdivide,trial13,bsxfun(@plus,[ eta],1));
64 Sb21=bsxfun(@rdivide,trial21,bsxfun(@plus,[ eta],1));Sb22=bsxfun(@rdivide,trial22,
65 bsxfun(@plus,[ eta],1));Sb23=bsxfun(@rdivide,trial23,bsxfun(@plus,[ eta],1));
66 Sb31=bsxfun(@rdivide,trial31,bsxfun(@plus,[ eta],1));Sb32=bsxfun(@rdivide,trial32,
67 bsxfun(@plus,[ eta],1));Sb33=bsxfun(@rdivide,trial33,bsxfun(@plus,[ eta],1));
68 %1*25 for each Sb element

```

```

65 Sbtensor=[Sb11; Sb12; Sb13; Sb21; Sb22; Sb23;Sb31; Sb32; Sb33];
66 normSb=sqrt (sum (Sbtensor.^2));
67
68 tic;
69 while G<1
70 stress11=load*sin ((n)*2*pi/stepnumber);
71 m=1/3*sum (stress11+0+0);
72 dev1=[stress11 0 0 ;0 0 0 ;0 0 0 ]-m*diag ([1,1,1]);
73 dev11=dev1(1,1); dev12=dev1(1,2); dev13=dev1(1,3);
74 dev21=dev1(2,1); dev22=dev1(2,2); dev23=dev1(2,3);
75 dev31=dev1(3,1); dev32=dev1(3,2); dev33=dev1(3,3);
76
77 stress11=load*sin ((n+1)*2*pi/stepnumber);
78 m=1/3*sum (stress11+0+0);
79 devn=[stress11 0 0;0 0 0;0 0 0]-m*diag ([1,1,1]);
80 dev11g=devn(1,1); dev12g=devn(1,2); dev13g=devn(1,3);
81 dev21g=devn(2,1); dev22g=devn(2,2); dev23g=devn(2,3);
82 dev31g=devn(3,1); dev32g=devn(3,2); dev33g=devn(3,3);
83
84 trial11=bsxfun (@plus ,Sb11 ,(dev11g-dev11)); trial12=bsxfun (@plus ,Sb12 ,( dev12g-dev12));
     trial13=bsxfun (@plus ,Sb13 ,( dev13g-dev13));
85 trial21=bsxfun (@plus ,Sb21 ,( dev21g-dev21)); trial22=bsxfun (@plus ,Sb22 ,( dev22g-dev22));
     trial23=bsxfun (@plus ,Sb23 ,( dev23g-dev23));
86 trial31=bsxfun (@plus ,Sb31 ,( dev31g-dev31)); trial32=bsxfun (@plus ,Sb32 ,( dev32g-dev32));
     trial33=bsxfun (@plus ,Sb33 ,( dev33g-dev33));
87 trialtensor=[trial11; trial12; trial13; trial21; trial22; trial23; trial31; trial32;
     trial33];
88 normtrial=sqrt (sum (triantensor.^2));
89 [ eta]=bsxfun (@minus ,bsxfun (@times ,normtrial/y ,s) ,1); %1*25
90 eta (eta <0)=0;
91
92 Sb11=bsxfun (@rdivide ,trial11 ,bsxfun (@plus ,[ eta] ,1));Sb12=bsxfun (@rdivide ,trial12 ,
     bsxfun (@plus ,[ eta] ,1));Sb13=bsxfun (@rdivide ,trial13 ,bsxfun (@plus ,[ eta] ,1));
93 Sb21=bsxfun (@rdivide ,trial21 ,bsxfun (@plus ,[ eta] ,1));Sb22=bsxfun (@rdivide ,trial22 ,
     bsxfun (@plus ,[ eta] ,1));Sb23=bsxfun (@rdivide ,trial23 ,bsxfun (@plus ,[ eta] ,1));
94 Sb31=bsxfun (@rdivide ,trial31 ,bsxfun (@plus ,[ eta] ,1));Sb32=bsxfun (@rdivide ,trial32 ,
     bsxfun (@plus ,[ eta] ,1));Sb33=bsxfun (@rdivide ,trial33 ,bsxfun (@plus ,[ eta] ,1));

```

```

95 %1*25 for each Sb element
96 Sbtensor=[Sb11; Sb12; Sb13; Sb21; Sb22; Sb23;Sb31; Sb32; Sb33];
97 normSb=sqrt(sum((Sbtensor.^2)));
98
99 Ws=(bsxfun(@minus, normtrial, bsxfun(@rdivide, y,[ s])) <=0).*...
100 (0) +...
101 (bsxfun(@minus, normtrial, bsxfun(@rdivide, y,[ s])) >0).*...
102 ((E-k)*(1+nu)/(2*E*(E+k*nu))*bsxfun(@times,[ weight],bsxfun(@rdivide,bsxfun(@times,
103 bsxfun(@minus, normtrial, bsxfun(@rdivide, y,[ s])),y),[s]))));
104 W= sum(Ws);
105 G = G\W/WF;
106 D=1-(1-G.^((1/(1-alp))).^(1/(gam + 1)));
107
108 % hold on;
109 % yield1=plot (n,y*s(1).^-1, 'LineStyle', 'none', 'LineWidth', 1, 'Marker', 'o', ...
110 % 'MarkerEdgeColor', 'none', 'MarkerFaceColor', 'c');
111 % Trial1=plot (n,sign(trial11(1))*normtrial(1), 'LineStyle', 'none', 'LineWidth',
112 % 1, 'Marker', '^', 'MarkerSize', 10, ...
113 % 'MarkerEdgeColor', 'r', 'MarkerFaceColor', 'r');
114 % Sb1=plot (n,sign(Sb11(1))*normSb(1), 'LineStyle', 'none', 'LineWidth', 1, 'Marker',
115 % 'v', 'MarkerSize', 10, ...
116 % 'MarkerEdgeColor', 'g', 'MarkerFaceColor', 'g');
117 % yield8=plot (n,y*s(8).^-1,'LineStyle', 'none', 'LineWidth', 1,'Marker', 'o', ...
118 % 'MarkerSize', 10, ...
119 % 'MarkerEdgeColor', 'none', 'MarkerFaceColor', 'b');
120 % Trial8=plot (n,sign(trial11(8))*normtrial(8), 'LineStyle', 'none', 'LineWidth',
121 % 1, 'Marker', '^', 'MarkerSize', 10, ...
122 % 'MarkerEdgeColor', [1 0.5 0], 'MarkerFaceColor',[1 0.5 0]);
123 % Sb8=plot (n,sign(Sb11(8))*normSb(8), 'LineStyle', 'none', 'LineWidth', 1, 'Marker',
124 % 'v', 'MarkerSize', 10, ...
125 % 'MarkerEdgeColor', 'k', 'MarkerFaceColor', 'k');
126 % DamageN=plot (t,D, 'LineStyle', 'none', 'LineWidth', 1, 'Marker', 'o', 'MarkerSize',
127 % 6, ...
128 % 'MarkerEdgeColor', 'none', 'MarkerFaceColor', 'm');

```

```

124
125 %-----Difference between cyclic load calculation and numerical method
126 %-----as function of time-----
127 % Gcyc = Gcyc+Wcyc/stepnumber/WF
128 % Dcyc=1-(1-Gcyc.^((1/(1-alp))).^((1/(gam + 1)));
129 % hold on
130 % Damagecyc=plot (t,D-Dcyc,'LineStyle', 'none', 'LineWidth', 1, 'Marker', 'o', ...
131 % 'MarkerSize', 6, ...
132 % 'MarkerEdgeColor', 'k', 'MarkerFaceColor', 'k');
133 n=n+1;
134 end;
135 toc;
136 t=n/stepnumber*1/f;
137 disp(['Time to failure is ' num2str(t) ' s.']);
138 sp=actxserver('SAPI.SpVoice');
139 sp.Speak('Job done');
140 % %-----chaboche method-----
141 % alp=0.5;
142 % D=0; %initial damage
143 % n=1; %initial recording point
144 % G = (1 - (1 - D).^(gam + 1)).^(1-alp);
145 % m=1/3*sum(diag(loadtensor));
146 % S1=loadtensor-m*diag([1,1,1]);
147 % sqrj1=1/2*sqrt(1/2)*norm(S1, 'fro');
148 % M=ff^1.233*(1-3*m/sigu);
149 % while G<1
150 % NF=1/((gam+1)*(1-alp))*(sqrj1/M)^(-gam);
151 % G = G+1/stepnumber/NF
152 % D=1-(1-G.^((1/(1-alp))).^((1/(gam + 1)));
153 % t=n/stepnumber*1/f;
154 % hold on;
155 % DamageC=plot (t,D, 'LineStyle', 'none', 'LineWidth', 1, 'Marker', 'o', 'MarkerSize'
156 % '6, ...
157 % 'MarkerEdgeColor', 'none', 'MarkerFaceColor', 'g');
158 % n=n+1;
159 % end
160 % %-----Cyclic load calculation-----

```

```

158 % Dcyc=0;
159 % n=1;
160 % Gcyc = (1 - (1 - Dcyc).^(gam + 1)).^(1-alp);
161 % Wcyc=4*(E-k)*(1+nu)*(b-1)/(E*(E+k*nu)*b*(b+1))*norm(loadtensor-(1/3*sum(diag(
162 loadtensor)))*diag([1,1,1]),'fro').^(b+1)*y.^((1-b));
163 % while Gcyc< 1
164 % Gcyc = Gcyc+Wcyc/stepnumber/WF
165 % Dcyc=1-(1-Gcyc.^((1/(1-alp))).^(1/(gam + 1));
166 % t=n/stepnumber*1/f;
167 % hold on
168 % Damagecyc=plot (t,Dcyc,'LineStyle','none','LineWidth',1,'Marker','o','
169 % MarkerSize',6,'...
170 % 'MarkerEdgeColor','none','MarkerFaceColor','b');
171 % n=n+1;
172 % end
173
174 %-----plot settings-----
175 grid on;
176 grid minor;
177 % axis([0 0.49 -0.04 0.04]);
178 set(gca,'FontSize',25);
179 hXLabel = xlabel('Number of steps','Fontsize',25);
180
181 hTitle = title('Microscopic stress evolution at 2 different scales ','Fontsize',25);
182 hYLabel = ylabel('Stress(Pa)', 'Fontsize',25);
183 hLegend=legend([yield1,Sb1,Trial1,yield8,Sb8,Trial8], '(\sigma_y-\lambda\sigma_H)/s_1
184 % at scale s_1','(S-b) at scale s_1',...
185 % '(S-b)_{trial} at scale s_1', '(\sigma_y-\lambda\sigma_H)/s_8 at scale
186 % s_8','(S-b) at scale s_8','(S-b)_{trial} at scale s_8');
187
188 % hTitle = title('Damage evolution comparison of three methods','Fontsize',30);
189 % hYLabel = ylabel('Damage','Fontsize',30);
190 % hLegend=legend([DamageN,DamageC,Damagecyc],'Numerical method','Chaboche method',...
191 % 'Cyclic load calculation');

```

```

190 % hTitle = title('Difference between cyclic load calculation and numerical method as
191 % function of time(time step=1/15000)', 'FontSize', 30);
192
193 % Adjust font
194 set(gcf, 'FontName', 'Helvetica')
195 set([hTitle, hXLabel, hYLabel], 'FontName', 'AvantGarde')
196
197 set([hXLabel, hYLabel], 'FontSize', 25)
198 set(hTitle, 'FontSize', 25, 'FontWeight', 'bold')
199 set([hLegend, gca], 'FontSize', 25)
200
201 % Adjust axes properties
202 set(gcf, 'Box', 'off', 'TickDir', 'out', 'TickLength', [.02 .02], ...
203 'XMinorTick', 'on', 'YMinorTick', 'on', 'YGrid', 'on', ...
204 'XColor', [.3 .3 .3], 'YColor', [.3 .3 .3], ...
205 'LineWidth', 1)
206
207 set(gcf, 'color', 'w'); %set figure background transparent
208 set(gca, 'color', 'w'); %set axis transparent
209
210 % Maximize print figure
211 set(gcf, 'outerposition', get(0, 'screensize'));
212 set(gcf, 'PaperPositionMode', 'manual');
213 set(gcf, 'PaperUnits', 'points'); %[ inches] | centimeters | normalized | points ]
214 set(gcf, 'PaperPosition', [0 0 1920 1080]); %set(gcf, 'PaperPosition',[left, bottom,
215 % width, height])
216 saveas(gcf, 'trialsin.png');
217 % saveas(gcf, 'damagesin.png');

```

```

1 ****
2 *
3 * CODING OF DAMAGE AND ENERGY EVOLUTION OF PSA LOAD (3 DIMENSIONAL)
4 *
5 ****
6 clear;clc;
7 dbstop if error
8 format long e
9
10 load('FX_RAVG.mat');
11 signal.data=double(signal.data);
12 forcex= transpose(signal.data);
13 load('FY_RAVG.mat');
14 signal.data=double(signal.data);
15 forcey= transpose(signal.data);
16 load('FZ_RAVG.mat');
17 signal.data=double(signal.data);
18 forcez= transpose(signal.data);
19 copy=1;
20 forcex=repmat(forcex, copy, 1);
21 forcey=repmat(forcey, copy, 1);
22 forcez=repmat(forcez, copy, 1);
23
24 %-----Arithmetic sequence between every recorded points
25 %-----%
26 ari=2; %insert (ari-1) points between the two limits
27 for i=2:(copy*802805)
28 %force(1+ari*(i-1):1+ari*i)=linspace(forceorigin(i),forceorigin(i+1),ari+1);
29 forcelx(1+ari*(i-2):1+ari*(i-1))=linspace(forcex(i-1),forcex(i),ari+1);
30 forcely(1+ari*(i-2):1+ari*(i-1))=linspace(forcey(i-1),forcey(i),ari+1);
31 forcelz(1+ari*(i-2):1+ari*(i-1))=linspace(forcez(i-1),forcez(i),ari+1);
32 end;
33 % ari*(i-1)+1 ;%the number of points
34 %-----build the stress tensor-----
35 A=1/6e4;
36 cx=10;

```

```

37 cy=60;
38 thetax=0.5;
39 thetay=0.6;
40 phix=0.3;
41 phiy=0.4;
42 stress11=1/A*(forcex+cx*forcex*cos(thetax)^2+cy*forcely*cos(thetay)^2);
43 stress12=1/A*(cx*forcex*cos(thetax)*sin(thetax)*cos(phix)+cy*forcely*cos(thetay)*sin(
44     thetay)*cos(phiy));
45 stress13=1/A*(cx*forcex*cos(thetax)*sin(thetax)*sin(phix)+cy*forcely*cos(thetay)*sin(
46     thetay)*sin(phiy));
47 stress21=stress12;
48 stress22=1/A*(cx*forcex*sin(thetax)^2*cos(phix)^2+cy*forcely*sin(thetay)^2*cos(phiy)
49     ^2);
50 stress23=1/A*(cx*forcex*sin(thetax)^2*cos(phix)*sin(phix)+cy*forcely*sin(thetay)^2*
51     cos(phiy)*sin(phiy));
52 stress31=stress13;
53 stress32=stress23;
54 stress33=1/A*(cx*forcex*sin(thetax)^2*sin(phix)^2+cy*forcely*sin(thetay)^2*sin(phiy)
55     ^2);
56 % [max(stress11) max(stress12) max(stress13);
57 % max(stress12) max(stress22) max(stress23);
58 % max(stress23) max(stress13) max(stress33);]
59 % [mean(stress11) mean(stress12) mean(stress13);
60 % mean(stress12) mean(stress22) mean(stress23);
61 % mean(stress23) mean(stress13) mean(stress33);]

62 x=[-0.99555697 -0.976663921 -0.942974571 -0.894991998 -0.833442629 -0.759259263
63 -0.673566368...
64 -0.57766293 -0.473002731 -0.361172306 -0.243866884 -0.122864693 0 0.122864693
65 0.243866884 0.361172306...
66 0.473002731 0.57766293 0.673566368 0.759259263 0.833442629 0.894991998 0.942974571
67 0.976663921...
68 0.99555697];
69 weight=[0.011393799 0.026354987 0.040939157 0.054904696 0.068038334
70 0.0801407 0.091028262...
71 0.100535949 0.108519624 0.114858259 0.119455764 0.122242443
72 0.123176054 0.122242443 0.119455764...

```

```

64 0.114858259      0.108519624      0.100535949      0.091028262      0.0801407
    0.068038334      0.054904696      0.040939157...
65 0.026354987      0.011393799];
66 % x= xlsread( 'Gauss-Legendre Quadrature' , 'Sheet1' , 'b1:z1' );
67 % weight= xlsread( 'Gauss-Legendre Quadrature' , 'Sheet1' , 'b2:z2' );
68 y=6.38e8;           %macroscopic yield stress
69 lam=0.5;            %hydrostatic pressure sensitivity
70 E=2e11;             %Youngs modulus
71 k=6e8;              %hardening parameter
72 b=3;                %weakening scales distribution exponent
73 nu=0.3;              %poisson 's ratio
74 tt=2e8;              %torsion fatigue limit
75 ff=2.5e8;            %bending fatigue limit
76 ac=(tt-ff/sqrt(3))/(ff/3); %crossland criterial constant
77 bc=tt;              %crossland criterial constant
78 sigu=8e8;            %ultimite stress
79 gam=0.5;              %material parameter from Chaboche law(Wohler curve exponent)
80 samplerate=256;      %recorded samples per second
81
82
83 %-----Vectorization -----
84 tic;
85 WF=3e7;              %dissipated energy to failure per unit volume
86 alp=0.8;
87 D=0;                  %initial damage
88 n=1;                  %initial recording point
89 step=1/samplerate/ari;
90 t=n*step;
91 G = (1 - (1 - D).^(gam + 1)).^(1-alp);
92 %-----to get the the first Sb-----
93 m=1/3*sum(stress11(1)+stress22(1)+stress33(1));
94 yield(1)=y-lam*m; %macro yield strength considering mean stress effect
95 dev1=[stress11(1) stress12(1) stress13(1);stress21(1) stress22(1) stress23(1);stress31
    (1) stress32(1) stress33(1)]-m*eye(3);
96 dev11=dev1(1,1); dev12=dev1(1,2); dev13=dev1(1,3);
97 dev21=dev1(2,1); dev22=dev1(2,2); dev23=dev1(2,3);
98 dev31=dev1(3,1); dev32=dev1(3,2); dev33=dev1(3,3);

```

```

99
100 trial11=dev11; trial12=dev12; trial13=dev13;
101 trial21=dev21; trial22=dev22; trial23=dev23;
102 trial31=dev31; trial32=dev32; trial33=dev33;
103 trialtensor=[trial11; trial12; trial13; trial21; trial22; trial23; trial31; trial32;
104 trial33];
105 normtrial(1,1:length(x))=sqrt(sum(trialtensor.^2));
106 s= (x/2+1/2).^(1/(1-b)); %1*25
107 eta=bsxfun(@minus, bsxfun(@times, normtrial(1,1:length(x))/yield(1),s),1); %1*25
108 eta(eta<0)=0;
109
110 Sb11=bsxfun(@rdivide, trial11, bsxfun(@plus, eta,1)); Sb12=bsxfun(@rdivide, trial12, bsxfun(
111 @plus, eta,1)); Sb13=bsxfun(@rdivide, trial13, bsxfun(@plus, eta,1));
112 Sb21=bsxfun(@rdivide, trial21, bsxfun(@plus, eta,1)); Sb22=bsxfun(@rdivide, trial22, bsxfun(
113 @plus, eta,1)); Sb23=bsxfun(@rdivide, trial23, bsxfun(@plus, eta,1));
114 Sb31=bsxfun(@rdivide, trial31, bsxfun(@plus, eta,1)); Sb32=bsxfun(@rdivide, trial32, bsxfun(
115 @plus, eta,1)); Sb33=bsxfun(@rdivide, trial33, bsxfun(@plus, eta,1));
116 %1*25 for each Sb element
117 Sbtensor=[Sb11; Sb12; Sb13; Sb21; Sb22; Sb23; Sb31; Sb32; Sb33];
118 normSb(1,:)=sqrt(sum(Sbtensor.^2));
119 Ws=(bsxfun(@minus, normtrial(1,1:length(x)), bsxfun(@rdivide, yield(1),s))<=0).*...
120 (0)+...
121 (bsxfun(@minus, normtrial(1,1:length(x)), bsxfun(@rdivide, yield(1),s))>0).*...
122 ((E-k)*(1+nu)/(2*E*(E+k*nu))*bsxfun(@times, weight, bsxfun(@rdivide, bsxfun(@times, bsxfun(
123 @minus, normtrial(1,1:length(x)), bsxfun(@rdivide, yield(1),s)), yield(1)),s)));
124 W= sum(Ws);
125 G = G*W/WF; %1.322163316411401e-03
126 D(1)=1-(1-G.^((1/(1-alp))).^(1/(gam+1)));
127 while G<1
128 m=1/3*sum(stress11(n)+stress22(n)+stress33(n));
129 dev1=[stress11(n) stress12(n) stress13(n); stress21(n) stress22(n) stress23(n); stress31
130 (n) stress32(n) stress33(n)]-m*eye(3);
131 dev11=dev1(1,1); dev12=dev1(1,2); dev13=dev1(1,3);
132 dev21=dev1(2,1); dev22=dev1(2,2); dev23=dev1(2,3);
133 dev31=dev1(3,1); dev32=dev1(3,2); dev33=dev1(3,3);
134
135 m=1/3*sum(stress11(n+1)+stress22(n+1)+stress33(n+1));

```

```

130 yield(n+1)=y-lam*m; %macro yield strength considering mean stress effect
131 yield(yield<0)=0;
132 devn=[stress11(n+1) stress12(n+1) stress13(n+1);stress21(n+1) stress22(n+1) stress23(n
133 +1);stress31(n+1) stress32(n+1) stress33(n+1)]-m*eye(3);
134 dev11g=devn(1,1); dev12g=devn(1,2); dev13g=devn(1,3);
135 dev21g=devn(2,1); dev22g=devn(2,2); dev23g=devn(2,3);
136 dev31g=devn(3,1); dev32g=devn(3,2); dev33g=devn(3,3);
137
138 trial11=bsxfun(@plus,Sb11,(dev11g-dev11)); trial12=bsxfun(@plus,Sb12,(dev12g-dev12));
139 trial13=bsxfun(@plus,Sb13,(dev13g-dev13));
140 trial21=bsxfun(@plus,Sb21,(dev21g-dev21)); trial22=bsxfun(@plus,Sb22,(dev22g-dev22));
141 trial23=bsxfun(@plus,Sb23,(dev23g-dev23));
142 trial31=bsxfun(@plus,Sb31,(dev31g-dev31)); trial32=bsxfun(@plus,Sb32,(dev32g-dev32));
143 trial33=bsxfun(@plus,Sb33,(dev33g-dev33));
144 trialtensor=[trial11; trial12; trial13; trial21; trial22; trial23; trial31; trial32;
145 trial33];
146 normtrial(n+1,:)=sqrt(sum(trialtensor.^2));
147 eta=bsxfun(@minus,bsxfun(@times,normtrial(n+1,:)/yield(n+1),s),1); %1*25
148 eta(eta<0)=0;
149
150 Sb11=bsxfun(@rdivide,trial11,bsxfun(@plus,eta,1));Sb12=bsxfun(@rdivide,trial12,bsxfun(
151 @plus,eta,1));Sb13=bsxfun(@rdivide,trial13,bsxfun(@plus,eta,1));
152 Sb21=bsxfun(@rdivide,trial21,bsxfun(@plus,eta,1));Sb22=bsxfun(@rdivide,trial22,bsxfun(
153 @plus,eta,1));Sb23=bsxfun(@rdivide,trial23,bsxfun(@plus,eta,1));
154 Sb31=bsxfun(@rdivide,trial31,bsxfun(@plus,eta,1));Sb32=bsxfun(@rdivide,trial32,bsxfun(
155 @plus,eta,1));Sb33=bsxfun(@rdivide,trial33,bsxfun(@plus,eta,1));
156 %1*25 for each Sb element
157 Sbtensor=[Sb11; Sb12; Sb13; Sb21; Sb22; Sb23; Sb31; Sb32; Sb33];
158
159 normSb(n+1,:)=sqrt(sum((Sbtensor).^2));
160
161 Ws=(bsxfun(@minus,normtrial(n+1,:),bsxfun(@rdivide,yield(n+1),s))<=0).*...
162 (0)+...
163 (bsxfun(@minus,normtrial(n+1,:),bsxfun(@rdivide,yield(n+1),s))>0).*...
164 ((E-k)*(1+nu)/(2*E*(E+k*nu))*bsxfun(@times,weight,bsxfun(@rdivide,bsxfun(@times,bsxfun(
165 @minus,normtrial(n+1,:),bsxfun(@rdivide,yield(n+1),s)),yield(n+1)),s)));
166 W= sum(Ws);

```

```

158 G = GWF/WF;
159 D(n+1)=1-(1-G.^((1/(1-alp))).^((1/(gam + 1)));
160 t=n*step;
161 hold on;
162 yield1=plot (n,yield(n)*s(1).^-1, 'LineStyle', 'none','LineWidth', 1, 'Marker', 'o', 'MarkerSize', 10, ...
163 'MarkerEdgeColor', 'none', 'MarkerFaceColor' , 'c');
164 Trial1=plot (n,normtrial(n,1), 'LineStyle', 'none','LineWidth', 1,'Marker', '^', 'MarkerSize', 10, ...
165 'MarkerEdgeColor','r', 'MarkerFaceColor','r');
166 Sb1=plot (n,normSb(n,1), 'LineStyle', 'none','LineWidth', 1,'Marker', 'v', 'MarkerSize' ...
167 , 10, ...
168 'MarkerEdgeColor','g', 'MarkerFaceColor','g');
169 yield8=plot (n,yield(n)*s(8).^-1,'LineStyle', 'none','LineWidth', 1,'Marker', 'o', 'MarkerSize', 10, ...
170 'MarkerEdgeColor', 'none', 'MarkerFaceColor' , 'b');
171 Trial8=plot (n,normtrial(n,8), 'LineStyle', 'none','LineWidth', 1,'Marker', '^', 'MarkerSize',10, ...
172 'MarkerEdgeColor', [1 0.5 0], 'MarkerFaceColor',[1 0.5 0]);
173 Sb8=plot (n,normSb(n,8), 'LineStyle', 'none','LineWidth', 1,'Marker', 'v', 'MarkerSize' ...
174 , 10, ...
175 'MarkerEdgeColor','k', 'MarkerFaceColor','k');
176 % DamageN=plot (t,D, 'LineStyle', 'none', 'LineWidth', 1, 'Marker', 'o', 'MarkerSize' ...
177 '10, ...
178 % 'MarkerEdgeColor', 'none', 'MarkerFaceColor' , 'r');
179 n=n+1;
180 end;
181 toc;
182 disp(['Number of test points is ' num2str(n/ari+1) ' points.']);
183 NF=num2str(n);
184 testtime=num2str(t);
185 sp=actxserver('SAPI.SpVoice');
186 sp.Speak('Job done');
187 % hold on;

```

```

188 % yield1=plot ((1:n)*step,yield(1:n)*s(1).^-1, 'LineStyle', 'none', 'LineWidth', 1, 'Marker', 'o', 'MarkerSize', 10, ...
189 % 'MarkerEdgeColor', 'none', 'MarkerFaceColor', 'c');
190 % Trial1=plot ((1:n)*step,normtrial(1:n,1),'LineStyle', 'none', 'LineWidth', 1, 'Marker', '^', 'MarkerSize',10, ...
191 % 'MarkerEdgeColor', 'r', 'MarkerFaceColor', 'r');
192 % Sb1=plot ((1:n)*step,normSb(1:n,1),'LineStyle', 'none', 'LineWidth', 1,'Marker', 'v', 'MarkerSize',10, ...
193 % 'MarkerEdgeColor', 'g', 'MarkerFaceColor', 'g');
194 % yield8=plot ((1:n)*step,yield(1:n)*s(8).^-1,'LineStyle', 'none', 'LineWidth', 1,'Marker', 'o', 'MarkerSize', 10, ...
195 % 'MarkerEdgeColor', 'none', 'MarkerFaceColor', 'b');
196 % Trial8=plot ((1:n)*step,normtrial(1:n,8),'LineStyle', 'none', 'LineWidth', 1,'Marker', '^', 'MarkerSize',10, ...
197 % 'MarkerEdgeColor', [1 0.5 0], 'MarkerFaceColor',[1 0.5 0]);
198 % Sb8=plot ((1:n)*step,normSb(1:n,8),'LineStyle', 'none', 'LineWidth', 1,'Marker', 'v', 'MarkerSize', 10, ...
199 % 'MarkerEdgeColor', 'k', 'MarkerFaceColor', 'k');
200
201 % DamageN=plot ((1:n)*step,D(1:n),'LineStyle', 'none', 'LineWidth', 1, 'Marker', 'o', ...
202 % 'MarkerSize', 6, ...
203 % 'MarkerEdgeColor', 'none', 'MarkerFaceColor', 'r');
204 %-----plot settings-----
205 grid on;
206 grid minor;
207 set(gca , 'FontSize',25);
208 hXLabel = xlabel('t(s)', 'Fontsize', 25);
209
210 % hTitle = title('Damage evolution under multidimensional stress', 'Fontsize', 25);
211 % hYLabel = ylabel('D', 'Fontsize', 25);
212
213 hTitle = title('Microscopic stress evolution at 2 scales', 'Fontsize', 25);
214 hYLabel = ylabel('Stress(Pa)', 'Fontsize', 25);
215 hLegend=legend([yield1,Sb1,Trial1,yield8,Sb8,Trial8], '(\sigma_y-\lambda\sigma_H)/s_1
216 at scale s_1', '||S-b|| at scale s_1', ...
217 '||S-b||_{trial} at scale s_1', '(\sigma_y-\lambda\sigma_H)/s_8 at scale

```

```

s_{8}', '||S-b||           at scale s_{8}', '||S-b||_{trial}      at scale s_
{8}');

217 set([hLegend, gca], 'FontSize', 25)

218

219 % Adjust font
220 set(gca, 'FontName', 'Helvetica')
221 set([hTitle, hXLabel, hYLabel], 'FontName', 'AvantGarde')
222 set([hXLabel, hYLabel], 'FontSize', 25)
223 set(hTitle, 'FontSize', 25, 'FontWeight', 'bold')

224

225 % Adjust axes properties
226 set(gca, 'Box', 'off', 'TickDir', 'out', 'TickLength', [.02 .02], ...
227 'XMinorTick', 'on', 'YMinorTick', 'on', 'YGrid', 'on', ...
228 'XColor', [.3 .3 .3], 'YColor', [.3 .3 .3], ...
229 'LineWidth', 1)

230

231 set(gcf, 'color', 'w'); %set figure background transparent
232 set(gca, 'color', 'w'); %set axis transparent
233 % Maximize print figure
234 set(gcf, 'outerposition', get(0, 'screensize'));
235 set(gcf, 'PaperPositionMode', 'manual');
236 set(gcf, 'PaperUnits', 'points'); %[ inches] | centimeters | normalized | points ]
237 set(gcf, 'PaperPosition', [0 0 1920 1080]); %set(gcf, 'PaperPosition',[ left ,bottom ,
238 width ,height])
239 % saveas(gcf, 'damage3d.png');
239 saveas(gcf, 'trialreal3d.png');

```