Fatigue of metals, view point and prospect

Fatigue & structural durability
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What will be the response of a structure under a cyclic loading?
Mechanical engineering applications

Structures under cyclic loading

**Asymptotic states**
Asymptotic behavior of elasto-visco-plastic structures under thermomechanical cyclic loading:

- Elasticity
- Elastic shakedown
- Plastic shakedown
- Ratcheting

Stabilized response

![Diagram showing stress-strain relationship](image1)
![Diagram showing cyclic behavior](image2)
Mechanical engineering applications

High Cycle Fatigue (HCF)

- Stress amplitude
- Fatigue life
  - Elasticity & elastic shakedown

Low Cycle Fatigue (LCF)

- Plastic strain amplitude
- Fatigue life
  - Inelasticity, plastic shakedown

+ mean stress effect
  
  Multiaxial stress & strain effect

Small size defects & nonmetallic inclusions

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Fatigue of metals view point & prospect
High Cycle Fatigue (HCF)

Low Cycle Fatigue (LCF)

Objective life

Define a technical specification
Outline

- Shakedown theory / fatigue concept
  - High cycle fatigue and low cycle fatigue

- Mechanical engineering applications

- View point & prospect
Daniel C. Drücker, 1963

‘When applied to the microstructure, there is a hope that the concepts of endurance limit and shakedown are related and that fatigue failure can be related to energy dissipated in idealized material when shakedown does not occur’

A POSSIBLE APPROACH:

THE MATERIAL IS CONSIDERED AS A STRUCTURE (MICRO-STRUCTURE) SUBMITTED TO CYCLIC (VARIABLE) LOADINGS

- Mathematical Results (Melan, Koiter theorem...)
- Results on the Theory of polycristalline aggregates

E. Orowan, 1939,

Meso macro relationship
The shakedown theory / fatigue concept

Meso/Macro Scales, Cyclic behaviour, Shakedown

**HCF**

MACRO
Structure

**LCF**

Ratcheting

elastic shakedown

plastic shakedown

**MESO**

Grain

Energy dissipation!
The shakedown theory / fatigue concept

High Cycle Fatigue criterion

**first damage** → **grains**: Meso scale

Scale of material description for relevant parameters?

**Meso scale**

\[ \sigma, \varepsilon, \varepsilon^p \]

**Macro scale**

\[ \Sigma, E, E_p \]

**LIN-TAYLOR**: \( E = \varepsilon = \varepsilon_e + \varepsilon_p \)

\[ \sigma = l.L^{-1}. \Sigma + l.(\varepsilon_p - E_p) \]

If \( \varepsilon_p \rightarrow E_p, \rho \rightarrow 0, \)

\[ \sigma \approx \Sigma \text{ (SACHS)}, w_p \approx W_p \]

residual stress from loading cycle, strongly dependant of the loading path

\( \sigma = A : \Sigma + \rho \)  \( (\neq K : \Sigma) \)
At shakedown

\[ \sigma(x,t) = \Sigma(x,t) + \rho(x) \]

**Polycyclic Fatigue criterion:**

\[ f(\sigma(x,t)) < 0 \Rightarrow \text{no fatigue} \]

\[ f(\sigma(x,t)) \equiv a \tau(t) + p(t) \]

\[ \tau: \text{shear; } p = (\text{Trace } \sigma)/3 \]
The fatigue limit correspond to the limit of the elastic shakedown possibility of the material in the structure at the macroscopic scale and the mesoscopic scale.

Dang Van Criteria: Papadopoulos, ...

\[
\max_t \left\{ \tau(t) + ap(t) \right\} \leq b
\]
**LCF**: shakedown & dissipated energy

**MACRO**

Charkaluk & Constantinescu [2001]
Maitournam [2001]

• fatigue life determined by stabilized cycle at saturation point

**MESO** Skelton [1991]

• constant cumulated dissipated energy at saturation point

**LCF Criterion**

\[ N_f = N = f(W_{sat}) \]

\[ W = C.N^\beta \]
Research, on each shear plane, of the smallest circumscribed circle of the loading path.

The fatigue criterion is:

\[ \tau + \alpha \cdot p < B \]

- \( \tau \) : shear amplitude on the critical plane
- \( p \) : hydrostatic pressure

Computation of \( \tau(t) \) et \( p(t) \) at each instant.
HCF: Mechanical engineering applications

\[ \tau = -\alpha p + B \]

- Material data
- Stress path in the structure

\[ C_D = \frac{\tau_c + \alpha p - B}{B} \]

Shear amplitude

- Damage area
- Security area

Hydrostatic pressure

Material data

Stress path in the structure
HCF: Mechanical engineering applications

Mooring chains, deep offshore oil and gas

Operation loading
- Complex cyclic loading introduced in the calculation
- Tension variation
- In plane bending
- Out of plane bending

Results in the Dang Van diagram
FATIGUE CALCULATION OF A ROLLED CRANKSHAFT

ISO VALUES OF DANG VAN’S CRITERION

APPLIED LOAD

LOAD PATH AT CRITICAL POINT

RESIDUAL STRESSES FROM ROLLING

DESIGN CURVE

ROLLED

NOT ROLLED

Hydrostatic pressure (MPa)

Pression hydrostatique (MPa)

Shear (MPa)

Moments (N.m)

Contraintes résiduelles (MPa)

Profondeur (mm)

Angular position (°)

M/RR

M/θθ

M/ZZ

Contraintes résiduelles (MPa)

Profondeur (mm)

σRR

σθθ

σZZ

1000
800
600
400
200
0
-200
-400
-600

0
200
400
600
800

0
1
2
3
4

Fatigue of metals view point & prospect
Fatigue failure analysis of railroad vehicles wheel

Contact fatigue

Crack initiation only possible due to extremely severe braking which induced residual hoop stress > +400 MPa
**LCF**: Mechanical engineering applications

- Cyclic softening/hardening
- Stabilised behaviour
- Final failure

Stabilised cycle: representative of the cyclic life of the structure

Charkaluk and Constantinescu (2000)

Failure of the structure: initiation of a macroscopic crack

Skelton (1991)
LCF: Mechanical engineering applications

Material and structural behaviour model in structural calculation

- Representation of the material in the structure by constitutive equations with parameters of easy access
  - coupling with damage: leads to difficulties in
    - parameter identification
    - numerical implementation
    - calculation time
  - without coupling with damage
    - evolution cycle by cycle of the structure is sometime not necessary
    - identification on steady-state cycles and structural aged representativity
Exhaust pipe

LCF: Mechanical engineering application

stress (yy) in MPa

mechanical strain (yy)

-400 -300 -200 -100 0 100 200 300 400

-0.016 -0.014 -0.012 -0.010 -0.008 -0.006 -0.004 -0.002 0.000
**LCF**: Mechanical engineering applications

\[ W = C \cdot N^\beta \]

![Graph showing experimental vs. estimated lifetime with various data points and trend lines for different temperatures and mechanical conditions.](image)
**High Cycle Fatigue:**

the structure is globally elastic and fatigue phenomenon only initiates in some grains.

The fatigue limit corresponds to the shakedown limit at the meso scale

One can evaluate the local stress at the stabilized state:

from $\Sigma(x,t)$, we derive the local stress by constructing the smallest hypersphere that contains $\Sigma(x,t)$ and gives an estimation of the local stress tensor $\sigma(t) = \Sigma(t) + \rho$

From meso-macro relationship:

The fatigue criterion is given by:

$$\tau(t) + \alpha p(t) \leq B$$
Low Cycle Fatigue:
The macroscopic plastic strain is important and difference between $\varepsilon_p$ and $\varepsilon'_p$ decreases so that there is few differences between MACRO and MESO parameters.

The dissipated energy per cycle at the stabilised state is proposed as a fatigue criterion

$$W = C N^\beta$$

it is a scalar parameter easy to compute which leads sometimes to fairly good predictions on structures

PROSPECT.....
Dissipation, temperature & Shakedown limit

- Dissipative phenomena & cyclic plasticity: **temperature**
- Stabilized temperature evolutions: **asymptotic regime**
- **Shakedown limit** characterisation? Which **scale**? **Microstructure** influence?

Strohmeyer (1914)  
Luong (1995)  
Berthel (2007)

- Torsion alternée  
  Acier doux Bessemer  
  Calorimétrie
- Flexion rotative  
  Acier XC55  
  Thermographie IR (moyenne)
- Traction alternée  
  Acier Dual-Phase  
  Thermographie IR (champ macro.)
Does crack initiation correspond to a source of stored energy? Why nano materials get high strength?

- Coupled measure of strain fields & temperature
- Steel 316L overquenched polycrystalin (grains mm)
- Plasticity activation: critical resolved shear stress, stored energy
- Coupling test / numerical simulations: cristal thermoplasticity

Objective: microstructural effect on asymptotic regimes under cyclic loading?

Fatigue of metals view point & prospect

Monotonic loading Bodelot (2008), Seghir (2011)
2. Procédés de fabrication et tenue en fatigue (E. Pessard)

Probabilist multiaxial Criterion including two damage mechanisms depending on the type of the leading microstructural heterogeneities.

\[ P_F(\theta) = 1 - \exp \left[ - \frac{S}{S_0} \left\{ \frac{l_{m1} \times \tau_{a1}^{m1}}{T_0^{m1}} + \frac{l_{m2}(\theta) \times \Sigma_a^{m2}}{\Sigma_0^{m2}} \right\} \right] \]

\( \Sigma \)

Mean defect size

Test Direction

\( \sigma(\theta^\circ) / \sigma(0^\circ) \)

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Fatigue of metals view point & prospect
Polycrystalline aggregates modeling: micro scale

Numerical tools for 2D/3D Microstructure modeling

Artificial

EBSD2MESH

3D periodic microstructures

With a sufficiently large number of different microstructures investigated, a critical analysis of the multiaxial fatigue criteria has been undertaken, using the local mechanical quantities.
Nature is complex, there is still much to do to understand the microstructural effects on fatigue for actual and future engineering & industrial challenges.