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1-Day Seminar on

Pressure Vessel Integrity and Fatigue Failures

SIRRIS, Technologiepark 935, 9052 Zwijnaarde, Ghent, Belgium
www.sirris.be **(hosted by SIRRIS)**

Introduction to fatigue analysis

Guy BAYLAC	Yves SIMONET
GUY BAYLAC CONSULTANT	CETIM
guy_baylac@orange.fr	yves.simonet@cetim.fr

Overview of presentation

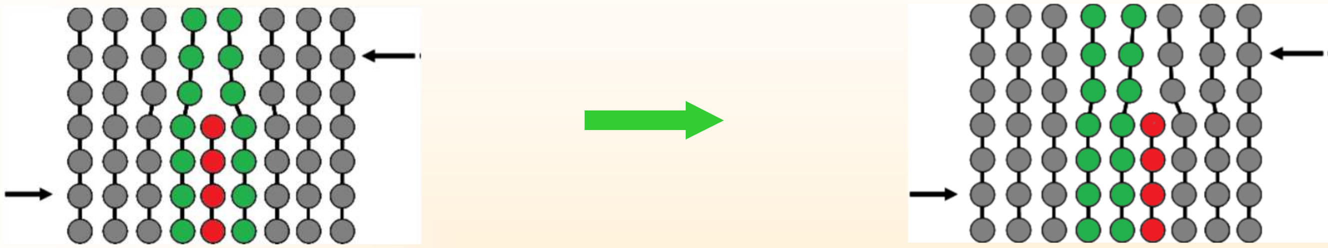
- Fatigue mechanism
- Fatigue curves for welded and unwelded components
- Influencing parameters
- Damage cumulation : Miner rule
- Conclusion

§17 Fatigue - Mechanism

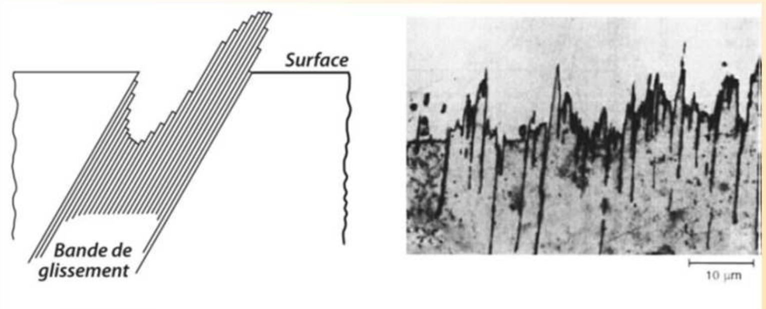
- **Fatigue of materials**
  - **Damage accumulation resulting of oscillating loadings (applications of $\Delta\sigma/\Delta\varepsilon$)**
- **Two types of fatigue behaviour**
  - **Fatigue associated to a great number of cycles (main object of Clause 17)**
    - **Most usual case**
    - **Stress less that the flow stress**
    - **Rupture without noticeable deformation**
  - **Plastic Fatigue associated to a low number of cycles (oligocyclic fatigue)**
    - **Case of the metallic wire folded and unfolded up to rupture**
    - **Acceptable only in well controlled zones where the deformation is self-limitative and does not cause a distortion of the component**
- **Fatigue mechanism**
  - **Mechanism with local character**
  - **Each load cycle creates a damage accumulation**
  - **Leading at term to**
    - **Crack initiation**
    - **Then crack propagation**
    - **Then to leak or failure**

§17 - Fatigue - Mechanism

- Dislocations move under effect of shear forces



- Slipping bands appear, creating intrusions-extrusions at the surface of the component



- A micro-crack resulting from stress concentration is formed
- If the stress range associated to the load variation is sufficient (greater than the endurance limit) the micro-crack propagates up to provoke rupture

  - In traction the crack propagates first at 45° (plan of maximum shear) then it changes its direction to progress perpendicularly to the direction of the most important principal stress (→direction associated to the force of maximum opening)

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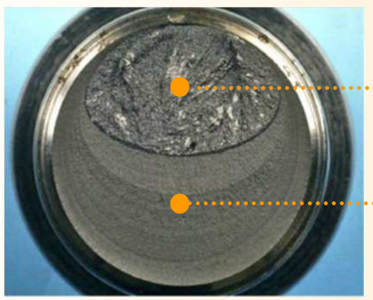
§17 - Fatigue - Facies

Macroscopic level

- Presence of two distinct zones :
  - A smooth zone which corresponds to the zone of fatigue cracking
  - A zone with grains associated to the brutal rupture happening at the end of the damage process



Traction

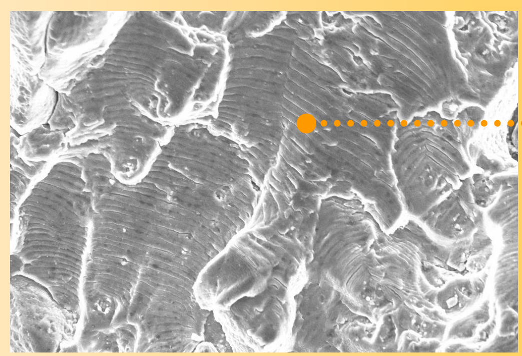
Alternate Bending

Rotative Bending

  - The ratio of the surfaces of smooth zones and zones with grains is an indication of the margin towards rupture for the applied loading

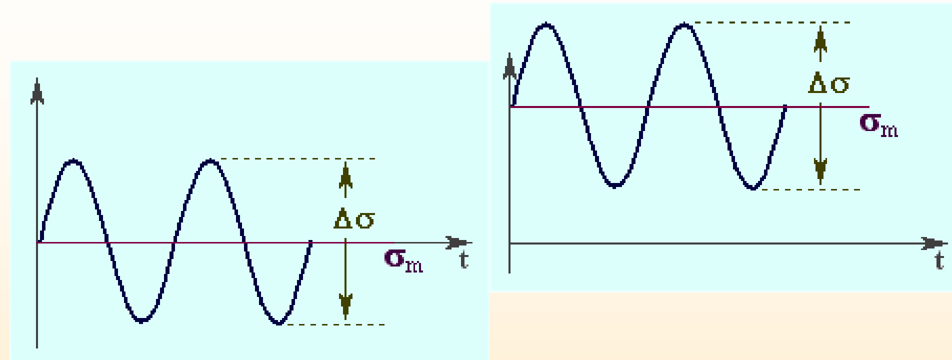
Microscopic level

- Presence fatigue scratches which represent crack progression at each load cycle

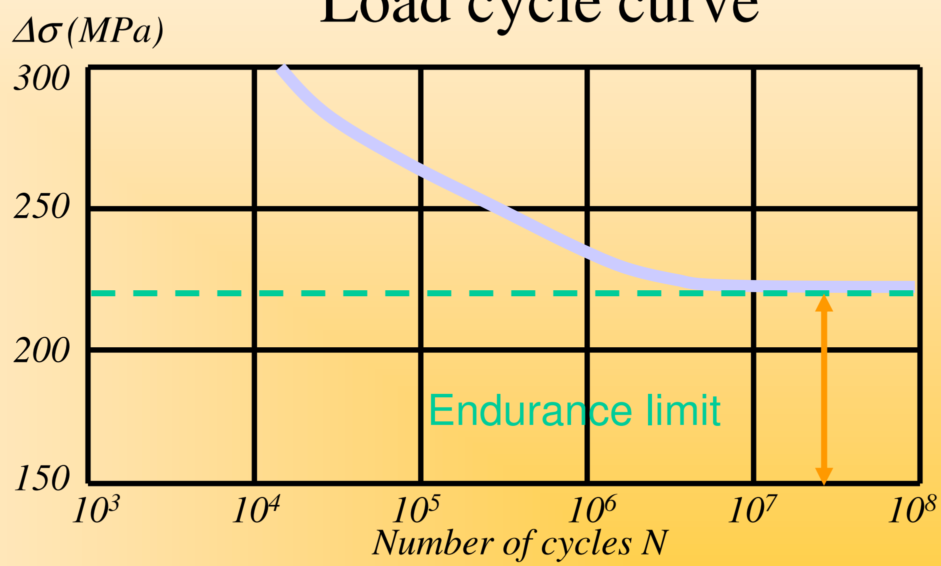


§17 - Fatigue – Fatigue strength

- **Characterization of fatigue strength**
  - Each load cycle is characterized by its associated stress range Δσ
  - For a given stress range there is a number of allowable cycles defined by the applicable fatigue curve (S-N curve)
  - Fatigue damage and break will appear only if Δσ is greater than the endurance limit
  - It is necessary to apply corrections to the values issued from the fatigue curve to take account of:
    - σ_m (because curve ↔ σ_m=0)
    - Stress concentrations
    - Scale factor
    - Surface state
    - Temperature



Load cycle curve



Fatigue curve

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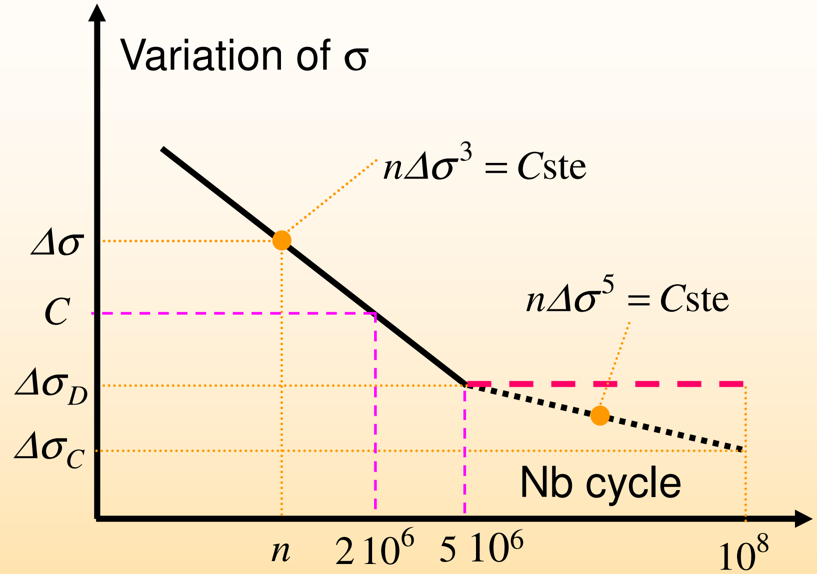
§17 - Fatigue – Fatigue curve - Welded Zones - 1

- Curves are issued from works of IIW (International Institute of Welding
- They come from tests performed on representative welded assemblies
- Each welded assembly is associated to a fatigue curve named « fatigue class ». A fatigue class is identified by a number. This number is the value of the stress range that the welded assembly can bear two millions of times.
- The curves take into account the influence of:
  - Local stress concentrations due to the geometry of the weld bead
  - Weld defects acceptable in manufacturing standards
  - Strong residual welding stresses
  - Non Destructive Testing (NDT) Procedures
- The stresses to be used to exploit these curves are the linearised stresses at the foot of the weld bead
  - In practice, the Tresca equivalent stress computed at the foot of the weld bead (on the skin of the wall) is used. The equivalent stress is determined from the components of the linearised tensor of the stresses.

§17 - Fatigue – Fatigue Curve - Welded Zone - 2



- Fatigue curve of Class «C»
  - Endurance limit $\Delta\sigma_D \rightarrow 5.10^6$ cycles
  - Cut-off limit $\Delta\sigma_C \rightarrow 10^8$ cycles
    - $\Delta\sigma < \Delta\sigma_C$: no fatigue damage
  - Below endurance limit
    - Damage if $\Delta\sigma_D$ cycles occur after cycles with $\Delta\sigma \geq \Delta\sigma_D$
    - No damage if it is not the case

- Curves for pressure vessels versus curves IIW
  - Curves of beads forbidden for pressure vessels were withdrawn
  - Fatigue curves have a probabilistic nature. The curve of the test corresponds to a probability of failure of 50%. The curves of the Codes correspond to a lower probability of failure. The curves for pressure vessels correspond to a lower probability of failure (0,14%) than the IIW curves which have been established for civil engineering
  - IIW curves have been established for priviledged directions (⊥ or // to the bead). In pressure vessels the lowest class IIW is considered and used with the equivalent stress (no more notion of direction).

§17 - Fatigue – Fatigue curve – Welded Zone - 3

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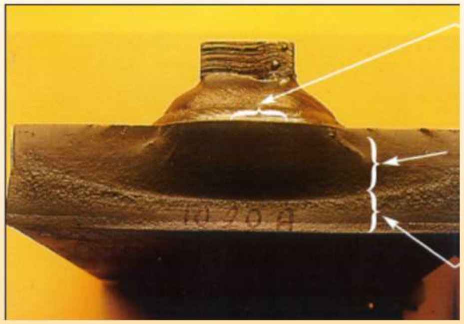
1 Rupture mode of welded zones

- Resistance of welded zones is less than that of the base metal
- Presence of geometrical singularities (→ stress concentrations)
  - Presence of defects (bead shape, ….)



- Crack initiation happens at bead foot
  - It may happen at the root of a bead laid down of small thickness (< 0,8×min{thicknesses of welded components})

- Fatigue with large number of cycles
  - Time to crack initiation is generally small. Life duration mainly depends on the speed of propagation of cracks. This propagation speed is not very dependent on the material (→ limited influence of R_m of the material)

- Oligocyclic Fatigue (NB : in principle curves do not apply directly !)
  - Stress concentrations and residual stresses have a reduced effect and the material resistance (R_m) has influence on the result

§17 - Fatigue – Fatigue Curve – Welded Zone - 4

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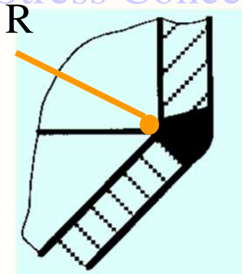
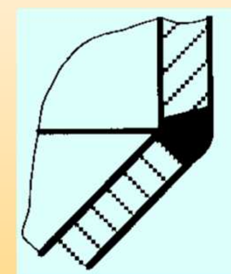
1 Influencing parameters to take into account

- Residual welding stresses (raw welding state) and mean stress
  - The presence of important residual stresses (near R_p) makes that the mean stress has a limited influence on the result (this influence is difficult to quantify $\rightarrow$ no correction de σ_m)
  - The presence of a corrective factor acting on the residual stresses (release, used welding process) is not taken into account
- Stress Concentration : effect included in the fatigue curve



Same linearised stress for the same load. The different stress concentration is translated into a change of class



Ground weld: class 100
sustains $\Delta\sigma$=100MPa 2×10^6 times

Not ground weld: class 80
sustains $\Delta\sigma$=80MPa 2×10^6 times

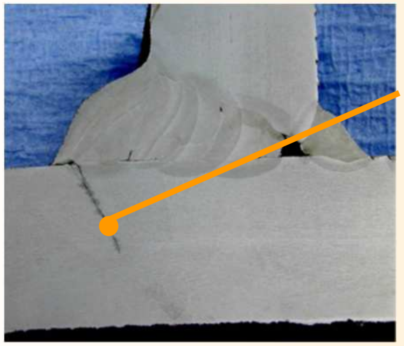
- Material strength
  - Limited influence in fatigue with great number of cycles ($\rightarrow R_m$ has no influence : the use of a high resistance steel does not modify the result)

- Scale factor: tests are performed on assemblies of thickness 25 mm ($\rightarrow$ the scale correction contains terms in $(25/e)^n$)

§17 - Fatigue - Fatigue Curve – Welded Zone- 5

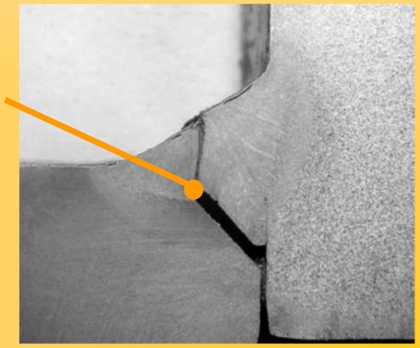
1 Inluencing parameters to take into account (continuation)

- Temperature
- Surface condition
  - For some beads the class used is a function of the presence or not of a finishing process (NB : No corrective factor in simplified fatigue analysis)
- Influence of weld defects and controls
  - For some beads the class used is function of the presence or not of a control (class is different if the zone can be controlled or not)
  - Fatigue curves come from tests performed on assemblies controlled to be exempt of major defects. Any defect has a crucial influence on the fatigue behaviour: a shape defect leads to a stress concentration, the other defects can be asssimilated to pre-existing cracks
  - Thus the presence of a control constitues one preliminary step necessary to any correct exploitation of the fatigue curves



Crack in foot caused by a shape defect

Crack in root caused by a lack of penetration



§17 - Fatigue – Fatigue Curve – Base Metal - 1

- Curves are inspired from those of AD-Merkblatt S2
- They are associated to a probability of failure de 0,1%. In comparison to curves associated to a probability of failure of 50% they incorporate:
  - A safety factor of 10 on the number of admissible cycles
  - A safety factor of 1,3 on the stress range
- The curves of AD use a safety factor of 1,5 on $\Delta\sigma$. This factor has been reduced because:
  - With 1,5 several curves were under the best curve of welded assemblies (Class 100)
  - EN 13445-3 recommends an inspection at the end of a period less than 20% of the allowable fatigue life (cf. EN 13445-3 Annexe M) while AD uses a period of 50% of life duration
- The stresses which must be used to exploit those curves are the total « effective » stresses (total$\rightarrow k_t \rightarrow k_f \rightarrow$ effective) in the zone under consideration
  - In practice the designer uses the equivalent stress of Tresca computed from the components of the stress tensor
- Calculation of total stresses : 2 possibilities
  - Use of linearised stresss multiplied by a factor of stress concentration (k_t) $\leftrightarrow$ use of a model which does not incorporate the exact geometry of the weld bead
  - Use of total stresses $\leftrightarrow$ use of a model which incorporates the exact geometry of the weld bead

§17 - Fatigue – Fatigue curve – Base Metal - 2

- The endurance limit corresponds to 2×10^6 cycles and cut-off to 10^8 cycles
- The curves show a fatigue life duration dominated by the time necessary to initiate a crack (→ response fonction of the resistance of the material)
- Influent Parameters to take into account
  - Mean stress
    - Life duration is shortened in presence of a mean stress of traction
    - If increases in presence of a mean stress of compression
    - The correction takes account of this phenomenon, it is that of AD-Merkblatt S2
  - Stress concentration: in case of use of linearised stresses
  - Resistance of material
    - The net of curves is parametered in fonction of the value of R_m
  - Scale factor : tests are performed on specimens of thickness 25 mm (→ scale correction contains terms in $(25/e)^n$)
  - Temperature
  - Surface
    - The correction is that of AD-Merkblatt S2

§17 - Fatigue - Courbe de fatigue – Métal de base - 3

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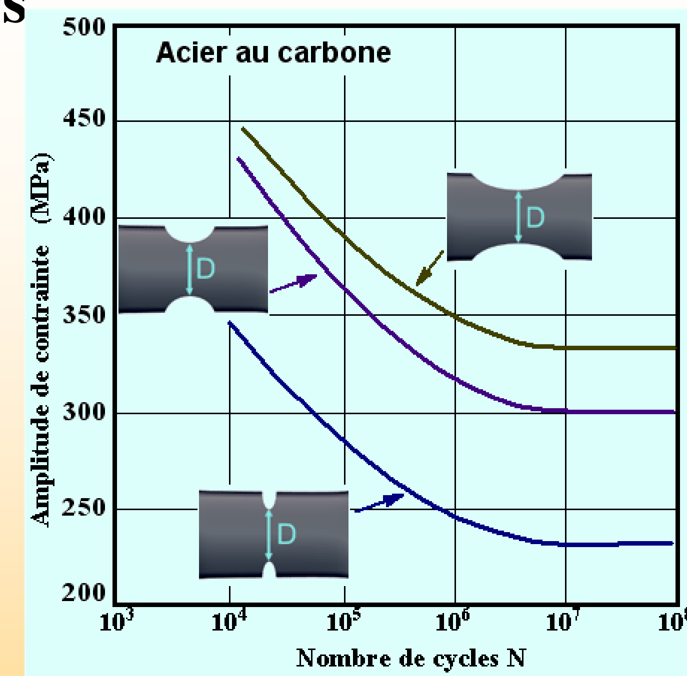
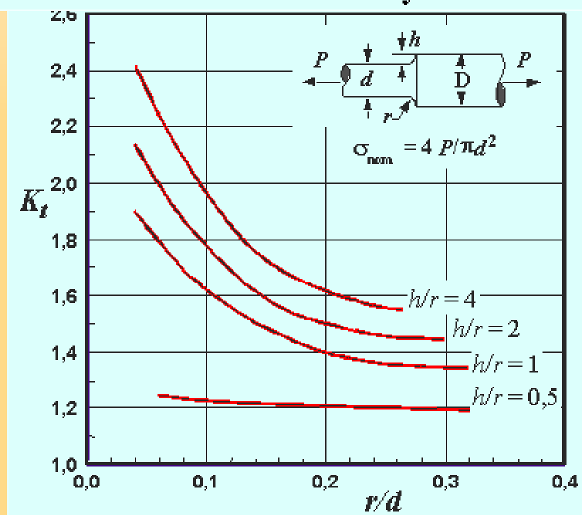
- Influent parameters to take into account (suite)
  - Pasticity correction
    - In the domain of oligocyclic fatigue, fatigue curves are established in fonction of the imposed strain variation $\Delta\varepsilon$
    - As long as $\Delta\sigma \leq 2\times R_{pt}$ $\Delta\sigma$ et $\Delta\varepsilon$ are proportionnal after adaptation and the $\Delta\varepsilon$ obtained from a calculation in linear elasticity in writing $\Delta\sigma = E\times\Delta\varepsilon$ is correct, it can be used directly to exploit the fatigue curves
    - If $\Delta\sigma > 2\times R_{pt}$ the $\Delta\varepsilon$ computed from a calculation performed in linear elasticity is under estimated (while $\Delta\sigma$ is over estimated). $\Delta\varepsilon$ must be corrected using a amplifying coefficient noted k_e (k_v for the thermal part- because the evolution profile of these stresses in the thickness is different - $k_v < k_e$)
    - By definition $k_e = \Delta\varepsilon_{ep} / \Delta\varepsilon_{elastique}$; $\Delta\varepsilon_{ep}$ is the real elastoplastic deformation
    - The correction coefficient k_e used is that of AD-Merkblatt S2
- Particular case of simplified rules
  - Only one fatigue curve
    - Curve of P235GH steel (lowest R_m)
  - The curve incorporates the effect of mean stress ($\rightarrow$ no correction of σ_m)
    - It is built for the largest mean stress acceptable: $\sigma_m = R_{pt} - (\Delta\sigma/2)$
  - The curve incorpores the effect of surface state ($\rightarrow$ no associated correction)
    - It is built for the state of delivery of the material

§17 - Fatigue – Influencing Parameters

- **Stress concentration**
  - Every stress concentration coming from the design of the component (notch, small radius of connexion, …) reduces fatigue resistance
  - The ratio betweeen σ maximum acting at the level of the section where is the concentration and the σ which would act uniformly at the level of the same section is called factor of concentration of stress (K_t) ($K_t > 1$)
  - The notch factor (K_f) is for a given life duration the ratio between acceptable Δσ of the component without notch and acceptable Δσ of the component with notch
    - $\Delta\sigma_{notch} = \Delta\sigma_{without—notch} / K_f$
    - $K_f > 1$ et K_f = fonction(K_t) in general $K_f < K_t$





1 Scale factor
  - Endurance limit is reduced when the size of the component is increased. A component of large size contains potentially more defects. This increases the number of sites of crack initiation.

§17 - Fatigue – Influencing Parameters - 2

- **Surface state**
  - **Endurance limit depends on the state of surface of the component. It reduces when the surface state is degraded.**
    - **A component having a bad surface state has more sites of crack initiation**
    - **This is important since the maximum stresses appear in general at the level of the skin**

- Effect of temperature
  - For current steels a temperature increase provokes a reduction of the endurance limit

- Influence of load history
  - A stress cycle of amplitude inferior to the endurance limit must be taken into account (it provokes a non-negligible damage) if it occurs after a stress cycle of a larger range than the endurance limit

§17 – Simplified Fatigue - Miner rule

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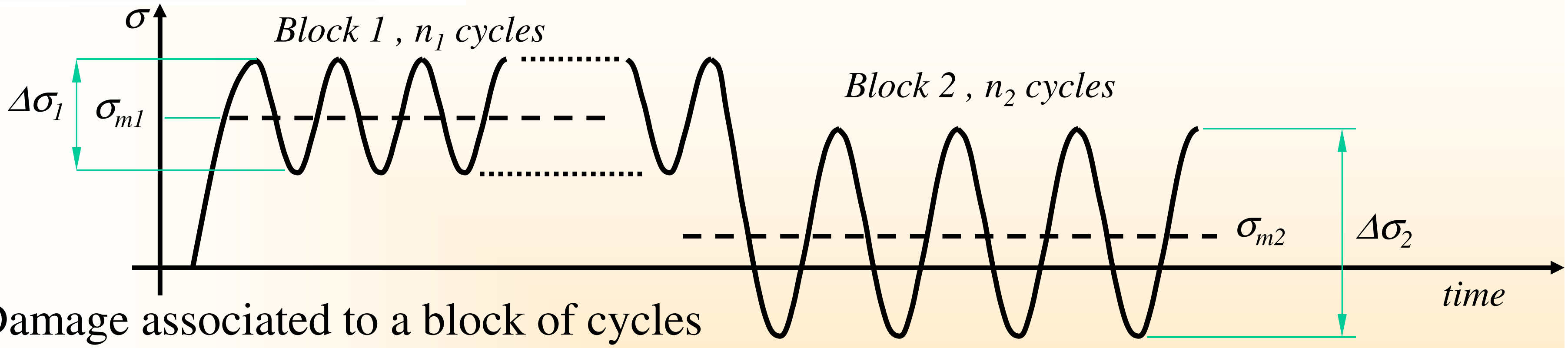
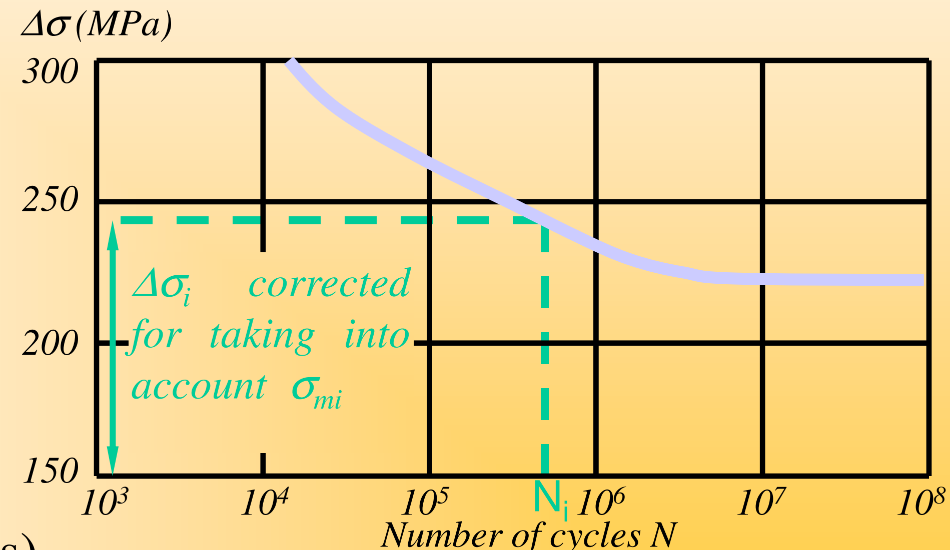
- **Decomposition in blocks of stress cycles**



- Damage associated to a block of cycles
  - Determination of the life N_i associated to the block of cycles i by use of the applicable fatigue curve
  - The fraction of life used by the block of cycles is (n_i/N_i)



- Cumulative damage
  - The fraction of life used by the blocks of cycles is $\sum(n_i/N_i)$
- Miner rule (linear cumulation of damages)
  - The component is totally damaged when $\sum(n_i/N_i) = 1$

Conclusion

- The different fatigue mechanisms to be considered in the construction of pressure vessels have been presented
- It has been shown how fatigue influencing parameters are taken into account in a conservative manner by the simplified analysis of Clause 17 of EN 13445

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Thank you for your attention