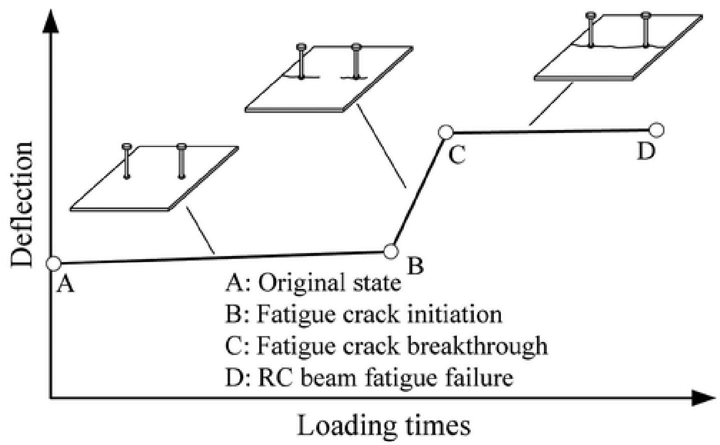

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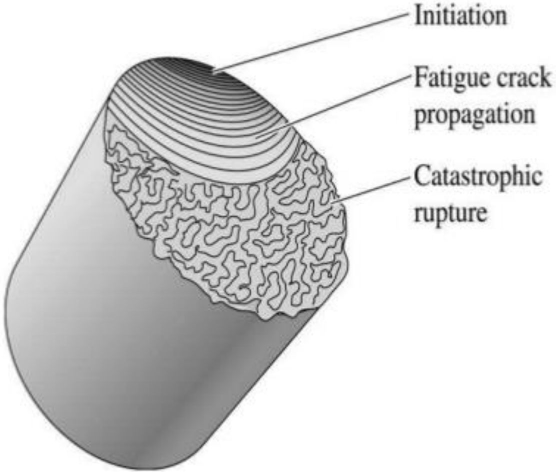
4.1 INTRODUCTION

4.1 INTRODUCTION / INTRODUCERE

FATIGUE represents the phenomenon of **decrease of strength** due to the application of **long term repeated loads** (fluctuating/cyclic stresses) in the order of 10^6 fluctuations/cycles, even if they produce lower stresses than the design static loads.

Fatigue starts from a defect in the material (i.e. a corrosion point). Around this area appear a crack, which starts to develops progressively until it causes a weakening of the section so that it can no longer resist the stress.



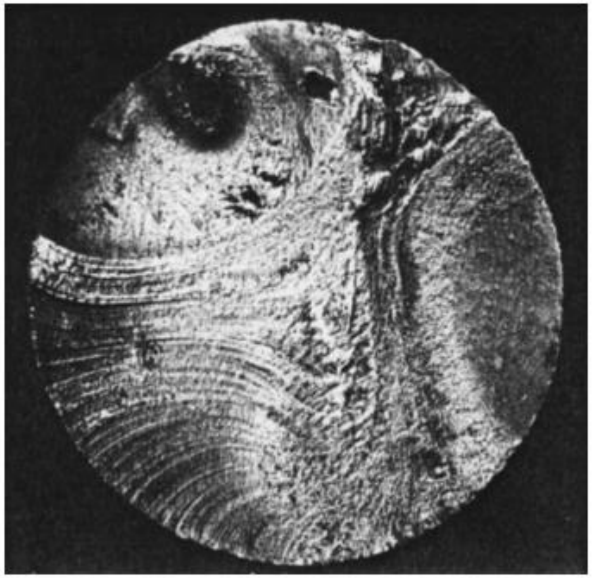
4.1 INTRODUCTION / INTRODUCERE

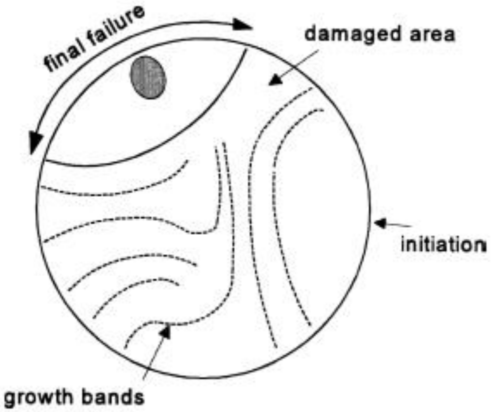
FATIGUE leads to brittle failure, regardless of the material ductility.

Fatigue failure are caused by **simultaneous actions** of

- **cyclic stress** → starts the crack
- **tensile stress** → produces crack growth (propagation)
- **plastic strain**

Fatigue failure occurs at stress level well below the static yield strength of the material.





Schijve J. – Fatigue of Structures and Materials (2009)

4.1 INTRODUCTION / INTRODUCERE

The fatigue phenomenon can be caused by mobile loads generated by industrial bridge cranes, road and railway convoys, or fix location equipments (with vibration)

bridge crane

road and railway convoys

Wind turbines

equipments with vibration

4.1 INTRODUCTION / INTRODUCERE

Each loading-unloading cycle produces degradations of both concrete and reinforcement, the accumulation of these degradations finally leading to element's failure under lower load intensities than those producing failure under static loads.

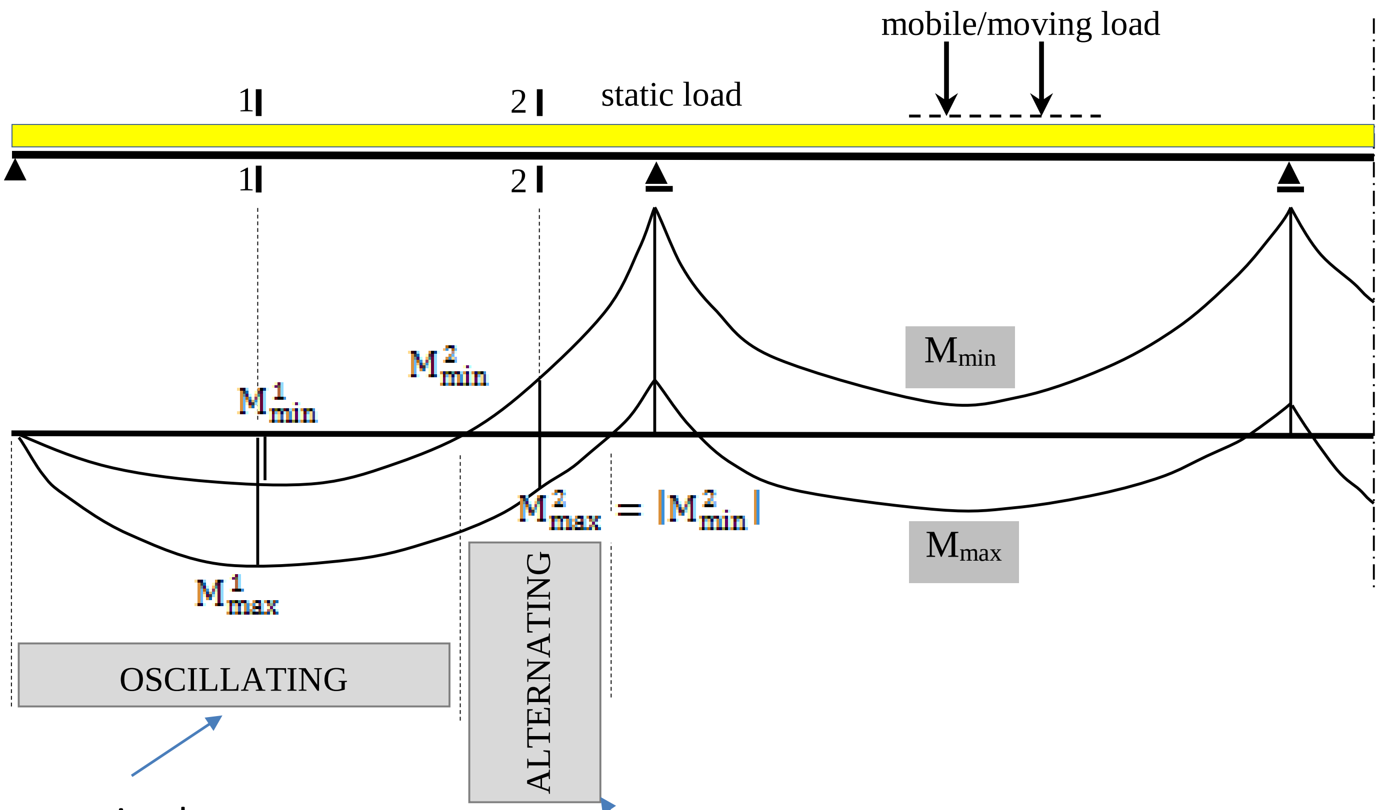
Assessment of **fatigue strength** of a reinforced concrete structure must be carried out **separately for concrete and reinforcement**.

From the **extreme loads** point of view **two types of cycles** are distinguished

- oscillating cycles

- alternating cycles

Example: continues beam



moment envelope curves

Stresses varying between certain limits without changing of action sense

It is producing changing of action sense, therefore deterioration of the concrete properties is more pronounced

4.1 INTRODUCTION / INTRODUCERE

The effect of repeated stresses on the material is practically the strength reduction.
This decreasing is decisively influenced by:

n	the number of cycles applied
σ_{max}	maximum value of the stress
$\Delta\sigma$	range (amplitude) of the cycles or $\Delta M = M_{max}(1-\rho)$
$\rho = \frac{\sigma_{min}}{\sigma_{max}}$	coefficient of asymmetry (or $\rho = \frac{M_{min}}{M_{max}}$)

4.2 BEHAVIOR UNDER FATIGUE / COMPORTAREA LA OBOSEALĂ

FATIGUE IN CONCRETE depends on:

- stress range $\Delta\sigma_c$
- number of cycles n
- stress level σ_c

FATIGUE OF STEEL depends on:

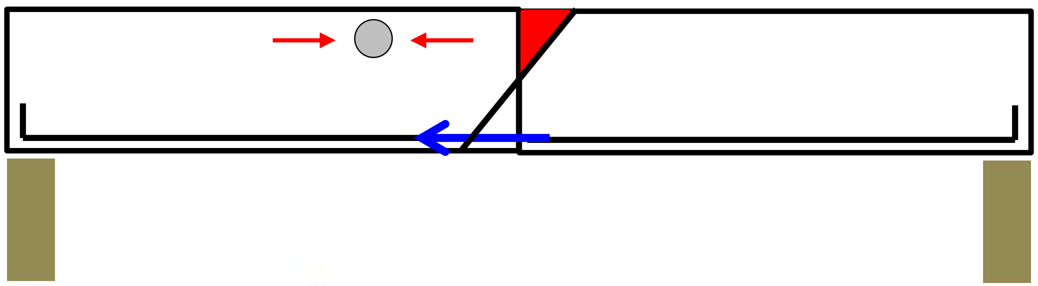
- stress range $\Delta\sigma_s$
- number of cycles n

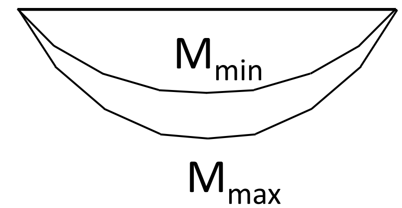
BEHAVIOR OF REINFORCED CONCRETE ELEMENTS depends on:

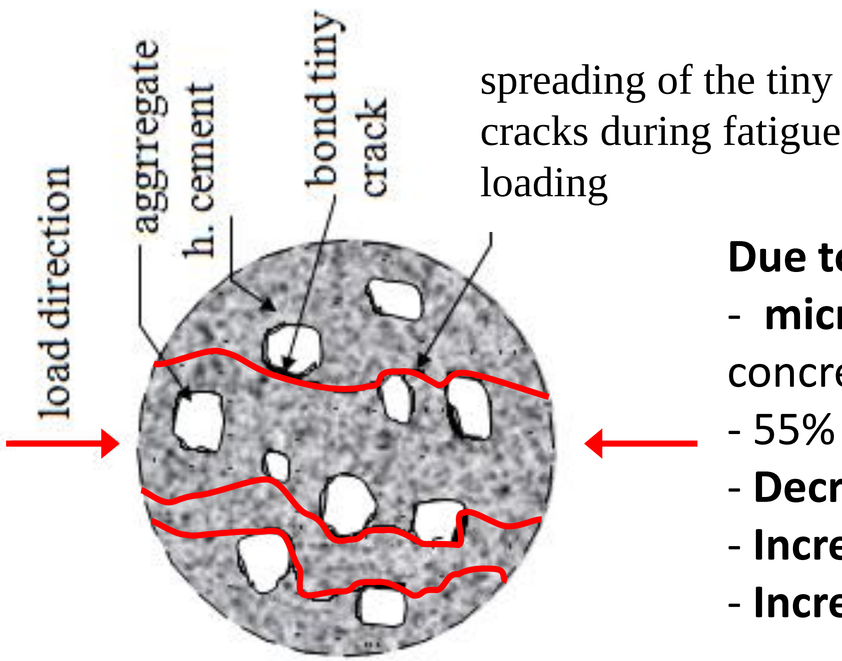
- concrete strength
- reinforcement strength
- bond

4.2 BEHAVIOR UNDER FATIGUE / COMPORTAREA LA OBOSEALĂ

CONCRETE BEHAVIOUR UNDER FATIGUE LOADING







Due to fatigue loading:

- **micro-cracking phenomenon** is accelerated leading to concrete crushing
- 55% **decreasing of compressive strength** for 10^6 cycles
- **Decreasing of element stiffness**
- **Increasing of crack number** and their **width**
- **Increasing of deformations**

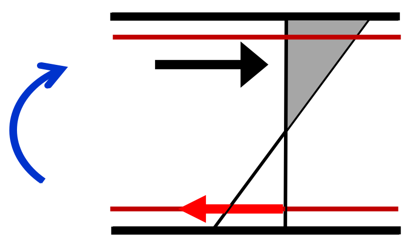
ALTERNATING CYCLES

TOP SIDE

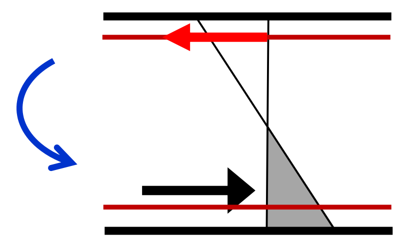
① accelerated micro-cracking

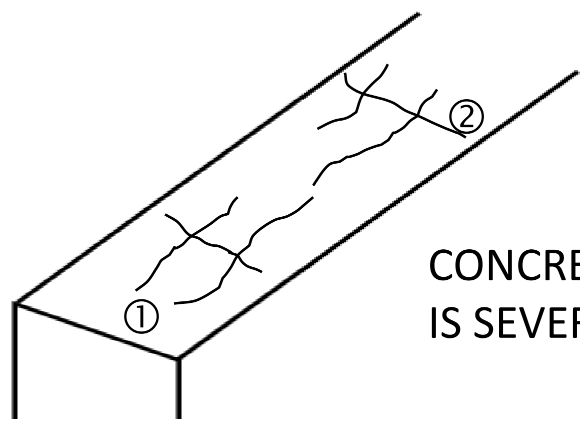
② cracks in tension

M_{max}



M_{min}





CONCRETE STRUCTURE IS SEVERELY DAMAGED

REINFORCEMENT BEHAVIOR UNDER FATIGUE LOADING

First FATIGUE crack appears:
- near transverse ribs
- previous mechanical damages
- at corroded areas

After initiation of the crack this **extends step by step** under the repeated load.

Reinforcements fails (break) when the active section became is too small.

Fatigue leads to a reduced tensile strength of concrete.
Bond is influenced by the concrete tensile strength.
→ Fatigue decrease bond strength.

4.2 BEHAVIOR UNDER FATIGUE / COMPORTAREA LA OBOSEALĂ

Failure of RC elements under fatigue loading is a brittle one, through:

Crushing of compression concrete in case of:

- elements with raised value of reinforcement percentage (bending & case I of compression)
- case II of compression (indifferent of concrete class and reinforcement quantity)
- low class concrete elements

Reinforcement failure in case of:

- elements with medium and low value of reinforcement percentage (bending & case I of compression)
- elements in tension
- reinforcements with low resistance to fatigue

Bond failure in case of:

- wrong detailing of reinforcement
- improper manufacturing
- low class concrete elements

4.1 INTRODUCTION

4.2 BEHAVIOUR UNDER FATIGUE

4.3 COMBINATION OF ACTIONS

4.4 REINFORCEMENT VERIFICATION

4.5 VERIFICATION OF COMPRESSED CONCRETE

4.6 VERIFICATION OF CONCRETE TO SHEAR

4.3 COMBINATION OF ACTIONS / COMBINAREA ACȚIUNILOR

For the calculation of the stresses the actions shall be divided into:

- non-cyclic actions (static)
- fatigue inducing cyclic actions

Combination of static actions

$$\sum G_{kj} + \Psi_{1,1} Q_{k,1} + \sum \Psi_{2,i} Q_{k,i}$$ - basic combination

(= frequent combination for SLS)

→ $\boldsymbol{\sigma_{min}}$

For cyclic action, to the effects of basic combination will be added the effects of repeated loading which cause fatigue

$$\left(\sum G_{kj} + \Psi_{1,1} Q_{k,1} + \sum \Psi_{2,i} Q_{k,i}\right) + Q_{fat}$$

fatigue

→ $\boldsymbol{\sigma_{max}}$

4.3 COMBINATION OF ACTIONS / COMBINAREA ACȚIUNILOR

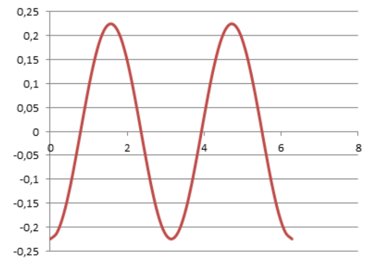
The **fatigue limit state** shall be verified **separately for concrete and reinforcement**, based on the minimum stress, σ_{min} calculated from the basic combination, and the maximum unit stress σ_{max} determined from the combination with the cyclic actions.

With the stresses so determined, the **amplitude** of the unit stress is determined as:

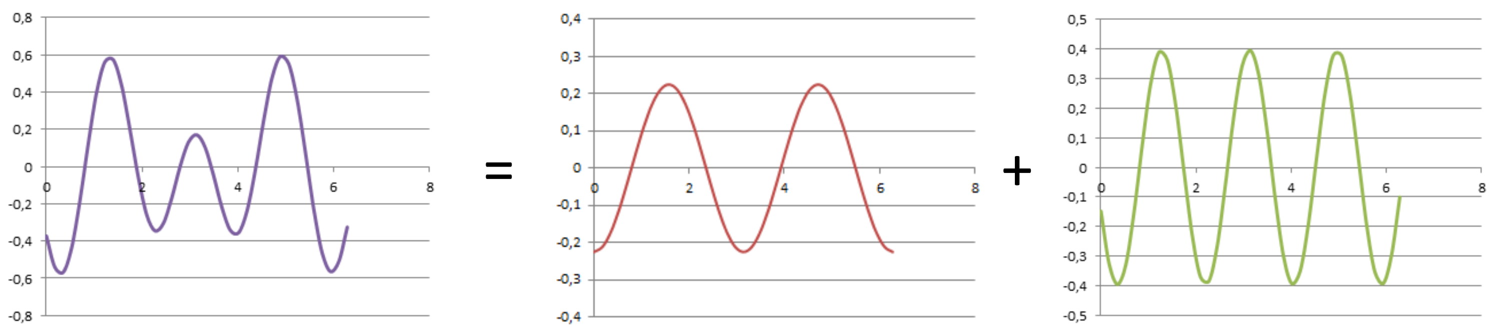
$$\Delta\sigma = \sigma_{max} - \sigma_{min}$$

4.3 COMBINATION OF ACTIONS / COMBINAREA ACȚIUNILOR

Basically, stress range may be constant for all loading cycles → a single level of amplitude



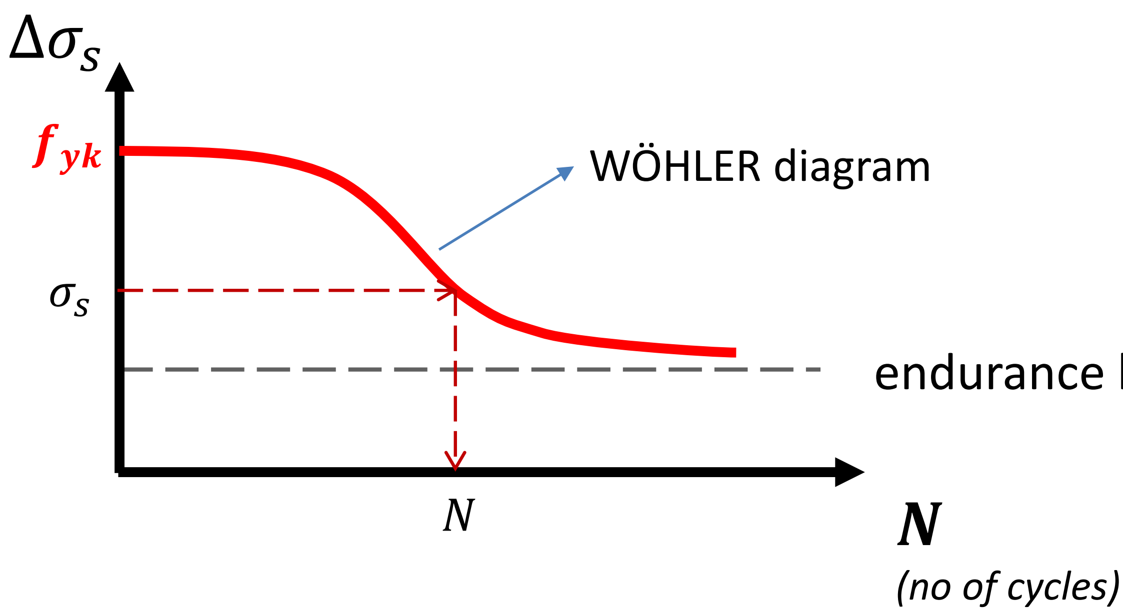
Usually, fatigue loading produces several different amplitudes: $\Delta\sigma_i$



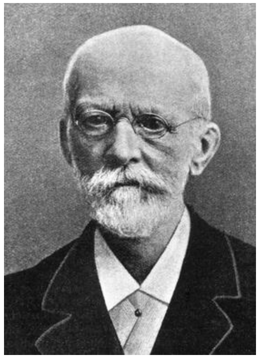
Such cases are described by amplitude spectrum, namely amplitude value: $\Delta\sigma_i$ and the number of applied cycles $\mathrm{n}(\Delta\sigma_i)$

4.4 REINFORCEMENT VERIFICATION / VERIFICAREA ARMĂTURILOR

WÖHLER has observed that steel strength decreases with the number of cycles applied and cycles amplitude ($\Delta\sigma_s$)



August WÖHLER



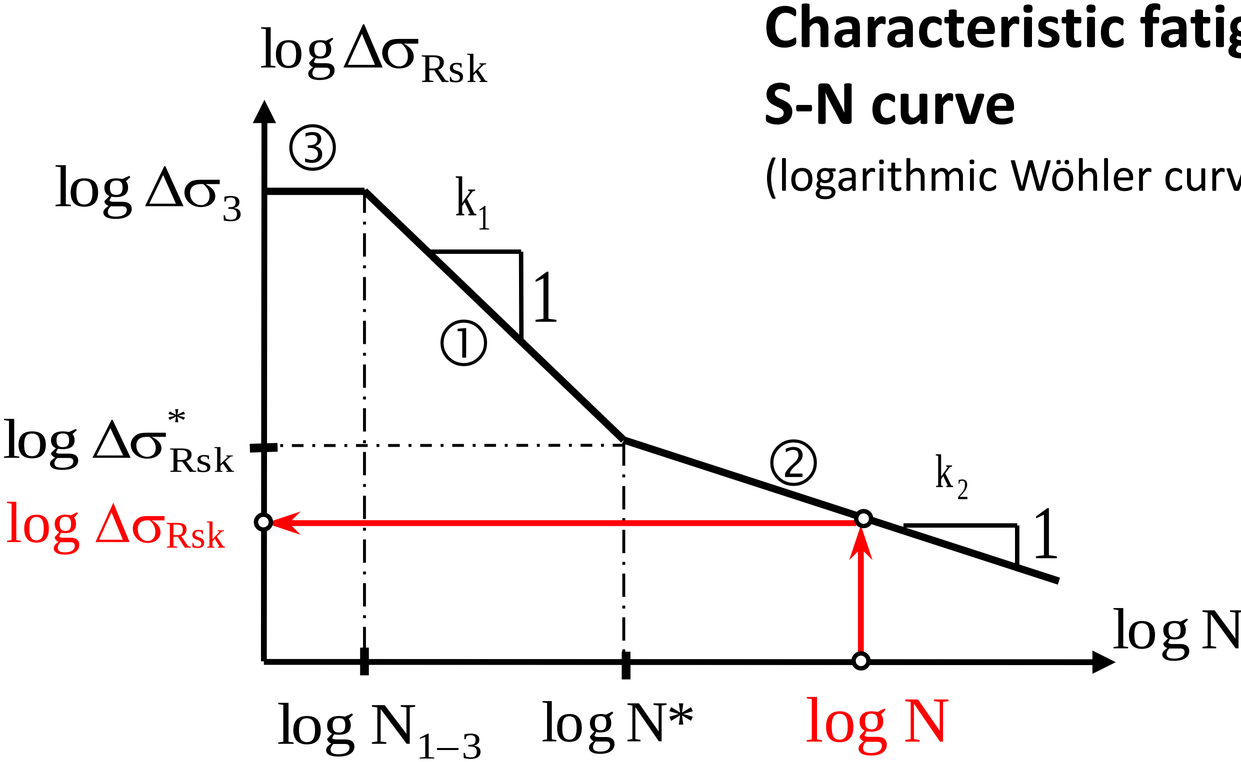
(1829 – 1914)

Smaller stress → greater number of cycles without steel failure

$$\Delta\sigma = \sigma_{max} - \sigma_{min}$$

4.4 REINFORCEMENT VERIFICATION / VERIFICAREA ARMĂTURILOR

Verification of the reinforcement fatigue limit is based on the amplitude that can be applied over N cycles without failure of reinforcement → this amplitude is defined as **characteristic amplitude**.



Characteristic fatigue strength curve

S-N curve

(logarithmic Wöhler curve, in which S representing $\Delta\sigma_s$)

$$\Delta\sigma_{Rsd} = \frac{\Delta\sigma_{Rsk}}{\gamma_{s,fat}}$$

4.4 REINFORCEMENT VERIFICATION / VERIFICAREA ARMĂTURILOR

Segments 1 & 2 are characterized by the relation:

$$(\Delta\sigma_s)^{k_1} \cdot N = (\Delta\sigma_s)^{k_2} \cdot N$$

Horizontal segment 3 corresponds to the situation in which the reinforcement is loaded up to the elastic limit (yield) under the basic combination plus the cyclic fatigue load

$$\Delta\sigma_3 = f_{yk} - \sigma_{smin}$$

Number of cycles corresponding to the connection point between segments 1 & 2:

$$N_{1-3} = N^* \left(\frac{\Delta\sigma^*_{Rsk}}{\Delta\sigma_3}\right)^{k_1}$$

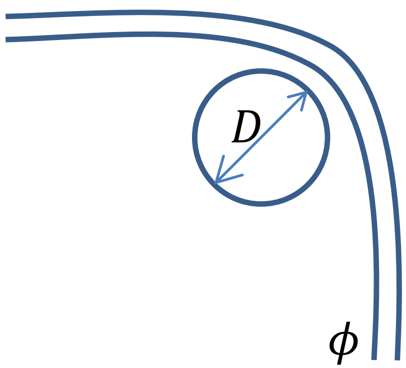
For practical calculation, the characteristic amplitude is obtained from the following table →

Number of cycles	$\Delta\sigma_{Rsk}$
$N_{1-3} < N \leq N^*$	$\Delta\sigma_{Rsk} = \Delta\sigma^*_{Rsk} \cdot \sqrt[k_1]{\frac{N^*}{N}}$
$N^* < N$	$\Delta\sigma_{Rsk} = \Delta\sigma^*_{Rsk} \cdot \sqrt[k_2]{\frac{N^*}{N}}$

4.4 REINFORCEMENT VERIFICATION / VERIFICAREA ARMĂTURILOR

Parameters of S-N curve for reinforced concrete

Type of reinforcement	N^*	Stress exponent		$\Delta\sigma^*_{Rsk}$ $[MPa]$ for N^* cycles
		k_1	k_2	
Strait bars	10^6	5	9	162.5
Bent bars	$10^6\zeta$	5ζ	9ζ	162.5ζ
Welded bars and fabrics	10^7	3	5	58.5
Mechanical couplers	10^7	3	5	35
Notes: $\zeta = 0.35 + 0.026D/\phi$; D = mandrel diameter ; ϕ = bar diameter				



Characteristic range (characteristic fatigue strength) $\Delta\sigma_{Rsk}$ does not depend on steel quality!

Good fatigue behavior is only ensured by limiting amplitude, regardless of the nature of the cycle (oscillating or alternating).

But if f_{yk} **increasing** then $\sigma_{s,max}$ **will be higher.**

4.4 REINFORCEMENT VERIFICATION / VERIFICAREA ARMĂTURILOR

Reinforcement verification for a <u>single amplitude</u> $\Delta\sigma_s$

- Calculation of σ_{min} stress from basic combination

$$\sum G_{kj} + \Psi_{1,1} Q_{k,1} + \sum \Psi_{2,i} Q_{k,i}$$

- Calculation of σ_{max} stress from combination which produces fatigue

$$\left(\sum G_{kj} + \Psi_{1,1} Q_{k,1} + \sum \Psi_{2,i} Q_{k,i} \right) + Q_{fat}$$

- Calculation of the amplitude $\Delta\sigma = \sigma_{max} - \sigma_{min}$

- Establishment the characteristics of S-N curve

cont

4.4 REINFORCEMENT VERIFICATION / VERIFICAREA ARMĂTURILOR

cont

- Determination of characteristic amplitude at fatigue $\Delta\sigma_{Rsk}$ in function of the number of cycles N;

- checking condition

$$\gamma_{F,fat}\Delta\sigma_s \leq \Delta\sigma_{Rsk} = \frac{\Delta\sigma_{Rsk}}{\gamma_{s,fat}}$$

Where

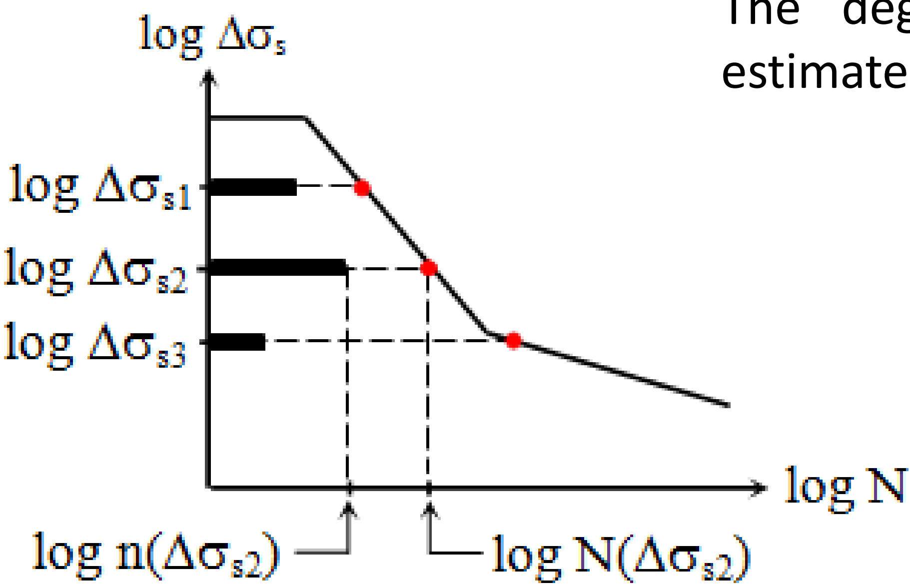
$\gamma_{F,fat} = 1{,}0$ N. A.

$\gamma_{s,fat} = 1{,}15$

Reinforcement verification for multiple cycles with variable amplitudes → is the usual situation of fatigue loading

Example: runway girders with multiple bridge crane from industrial halls

Palmgren-Miner Rule (superposing method)



Each amplitude produces some degradation.
The degradation caused by an amplitude is estimated by degradation index

$$d_i = \frac{n(\Delta\sigma_i)}{N(\Delta\sigma_i)}$$

$n(\Delta\sigma_i)$ - effective number of cycles
$N(\Delta\sigma_i)$ - number of cycles leading steel failure

4.4 REINFORCEMENT VERIFICATION / VERIFICAREA ARMĂTURILOR

Reinforcement verification for multiple cycles with variable amplitudes

Reinforcement has proper behaviour for fatigue if the degradations are limited for all the amplitudes:

$$D_{Ed} = \sum \frac{n(\Delta\sigma_i)}{N(\Delta\sigma_i)} < 1$$

D_{Ed}	degradation factor
i	number of the current amplitude
$\Delta\sigma_i$	current amplitude

with $N(\Delta\sigma_{si}) = N^* \left(\frac{\Delta\sigma^*_{Rsk} / \gamma_{s,fat}}{\gamma_{F,fat} \Delta\sigma_i} \right)^{k_1}$ pt $\gamma_{F,fat} \Delta\sigma_{si} \geq \frac{\Delta\sigma^*_{Rsk}}{\gamma_{s,fat}}$

cu $N(\Delta\sigma_{si}) = N^* \left(\frac{\Delta\sigma^*_{Rsk} / \gamma_{s,fat}}{\gamma_{F,fat} \Delta\sigma_i} \right)^{k_2}$ pt $\gamma_{F,fat} \Delta\sigma_{si} < \frac{\Delta\sigma^*_{Rsk}}{\gamma_{s,fat}}$

Verification with equivalent amplitude

The equivalent amplitude method consists of replacing multiple amplitudes with a constant amplitude $\Delta\sigma^*_{s,equ}$ corresponding to N* cycles

- for bridges $\Delta\sigma^*_{s,equ}(N^*)$ according to SR EN 1992-2

- for buildings $\Delta\sigma^*_{s,equ}(N^*) \approx \Delta\sigma_{s,max}$

Fatigue resistance is considered to be satisfactory if the condition is fulfilled:

$$\gamma_{F,fat}\Delta\sigma^*_{s,equ} \leq \frac{\Delta\sigma^*_{Rsk}}{\gamma_{s,fat}}$$

SIMPLIFIED PROCEDURE FOR VERIFICATION OF REINFORCEMENTS

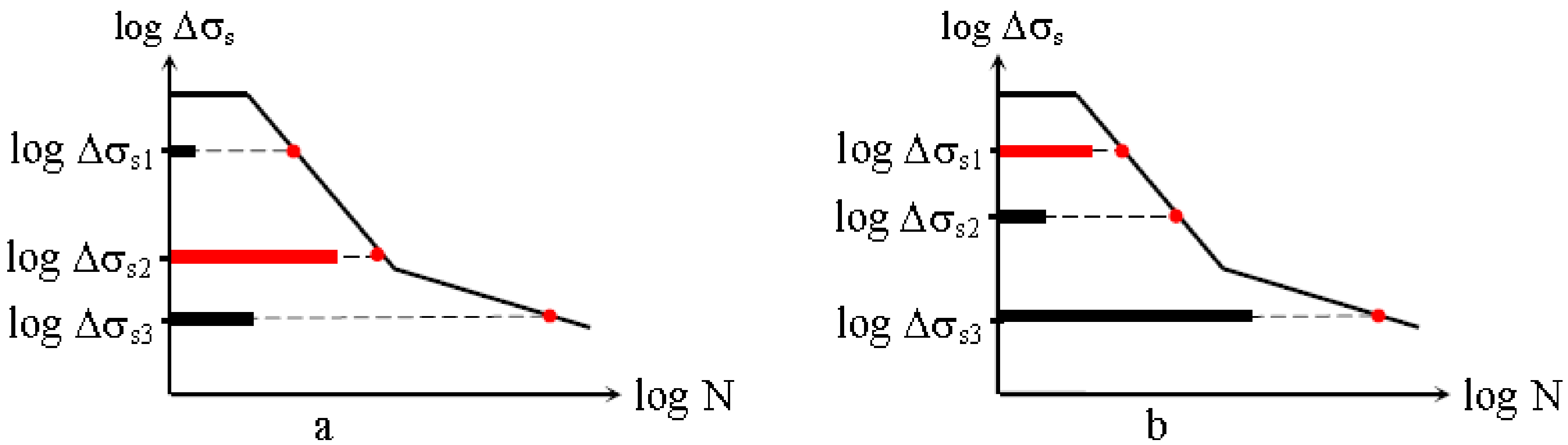
TENSION reinforcement is considered to have adequate fatigue strength if **under the most frequent cyclic load** (amplitude with the greatest number of repeats), **combined with the basic combination**, the following conditions are fulfilled:

$\Delta\sigma_{s,max} \leq 70\ MPa$ for unwelded bars

$\Delta\sigma_{s,max} \leq 35\ MPa$ for welded bars

As a simplification to the above, it is acceptable that $\Delta\sigma_s$ be calculated under the effect of the frequent combination of all actions (cyclic and non-cyclic). If the result of the calculation is favorable, other verifications are not necessary.

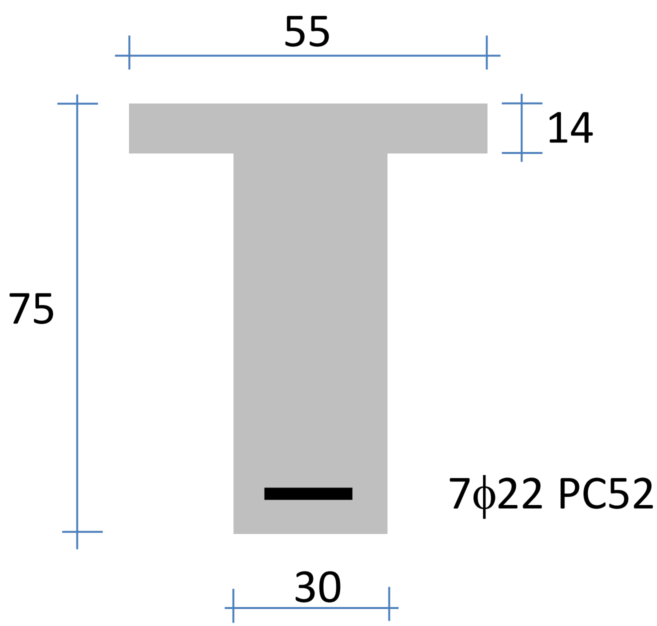
Why are such severe limitations needed?



Considering the amplitude with the most repetitions can represent a dangerous situation (a) or one in which an amplitude with a small number of repetitions ($\Delta\sigma_{s1}$) could generate more significant damage than the most frequent amplitude ($\Delta\sigma_{s3}$) (b).

4.4 REINFORCEMENT VERIFICATION / VERIFICAREA ARMĂTURILOR

Example



M_{max} = 290 kNm σ_{max} = 177 MPa

M_{min} = 50 kNm σ_{min} = 19 MPa

$\Delta\sigma_s$ = 158 MPa

To have $\Delta\sigma_s$ = 70 MPa

→   (10 … 12)ϕ22 PC52   or   h = 120 … 140 cm

→ THE SIMPLIFIED APPROACH IS NOT ECONOMICAL!!!

4.5 VERIFICATION OF COMPRESSED CONCRETE / VERIFICAREA BETONULUI COMPRIMAT

In EC2 there are provided two options to check fatigue resistance of concrete under compression.

Where appropriate Palmgren-Miner rule must be applied.

Design fatigue strength of compressed concrete, for N = 10^6 cycles:

$$f_{cd,fat} = k_1 \beta_{cc}(t_o) f_{ck}\left(1 - \frac{f_{ck}}{250}\right)$$

where

$k_1 = 0{,}85$	for 10^6 cycles from N. A.
$\beta_{cc}(t_o)$	coefficient which depends on the age of the concrete when the first load was applied
t_o	the age of the concrete (in days) at the start of the cyclic loading of concrete

4.5 VERIFICATION OF COMPRESSED CONCRETE / VERIFICAREA BETONULUI COMPRIMAT

Case 1: A satisfactory fatigue resistance may be assumed for concrete under compression induced by bending, if the following condition is fulfilled

$$E_{cd,max,equ} + 0{,}43\sqrt{1 - R_{equ}} \leq 1$$

$$R_{equ} = \frac{E_{cd,min,equ}}{E_{cd,max,equ}}$$ stress ratio

$$E_{cd,min,equ} = \frac{\sigma_{cd,min,equ}}{f_{cd,fat}}$$ maximum compressive stress level

$$E_{cd,max,equ} = \frac{\sigma_{cd,min,equ}}{f_{cd,fat}}$$ minimum compressive stress level

where

$\sigma_{cd,max,equ}$ - upper stress of the ultimate amplitude for N cycles

$\sigma_{cd,min,equ}$ - lower stress of the ultimate amplitude for N cycles

$f_{cd,fat}$ - design fatigue strength of concrete

4.5 VERIFICATION OF COMPRESSED CONCRETE / VERIFICAREA BETONULUI COMPRIMAT

Case 2: A simplified verification for fatigue of concrete can be applied if the following conditions are simultaneously respected:

$$\frac{\sigma_{c,max}}{f_{cd,fat}} \leq 0{,}5 + 0{,}45\frac{\sigma_{c,min}}{f_{cd,fat}}$$

$$\leq 0{,}9 \qquad \text{for } f_{ck} \leq 50\ MPa$$

$$\leq 0{,}8 \qquad \text{for } f_{ck} > 50\ MPa$$

where

$\sigma_{c,max}$ - maximum compressive stress under the frequent load combination (compression measured positive)

$\sigma_{c,min}$ - minimum compressive stress at the same fibre where $\sigma_{c,max}$ occurs

If $\sigma_{c,min}$ is a tensile stress ($\sigma_{c,min} < 0$), then should taken $\sigma_{c,min} = 0$.

4.6 VERIFICATION OF CONCRETE TO SHEAR

4.6 VERIFICATION OF CONCRETE TO SHEAR / VERIFICAREA BETONULUI LA FORFECARE

Members not requiring design shear reinforcement for the ultimate limit state, it may be assumed that the concrete resists fatigue due to shear effects when the following conditions are fulfilled:

1) for

$$\frac{V_{Ed,min}}{V_{Ed,max}} \geq 0$$

$$\frac{|V_{Ed,max}|}{|V_{Rdc}|} \leq 0{,}5 + 0{,}45\frac{|V_{Ed,min}|}{|V_{Rdc}|}$$

$$\leq 0{,}9 \quad \text{for } f_{ck} \leq 50\ MPa$$

$$\leq 0{,}8 \quad \text{for } f_{ck} > 50\ MPa$$

4.6 VERIFICATION OF CONCRETE TO SHEAR / VERIFICAREA BETONULUI LA FORFECARE

Members not requiring design shear reinforcement for the ultimate limit state, it may be assumed that the concrete resists fatigue due to shear effects when the following conditions are fulfilled:

2) for

$$\frac{V_{Ed,min}}{V_{Ed,max}} < 0$$

$$\frac{|V_{Ed,max}|}{|V_{Rdc}|} \leq 0{,}5 - \frac{|V_{Ed,min}|}{|V_{Rdc}|}$$

$V_{Ed,max}$ - design value of the maximum applied shear force under frequent load combination

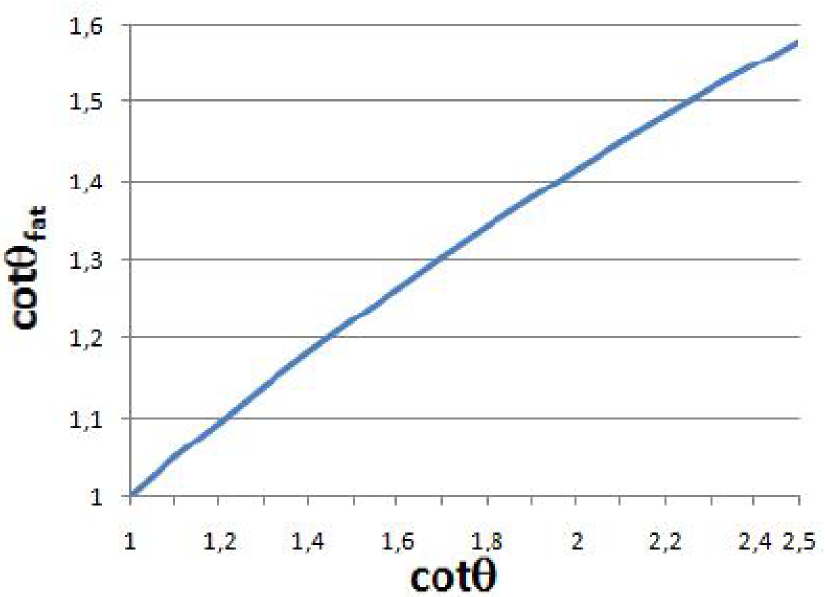
$V_{Ed,min}$ - design value of the minimum applied shear force under frequent load combination in the cross-section where $V_{Ed,max}$ occurs

V_{Rdc} - design value for shear-resistance of concrete without shear reinforcement

4.6 VERIFICATION OF CONCRETE TO SHEAR / VERIFICAREA BETONULUI LA FORFECARE

Members **requiring design shear reinforcement** for the ultimate limit state, design of shear reinforcement is based on the provisions given in chapter regarding the shear design, with the remark that the inclination of the compressive struts must be considered as:

$$\tan\theta_{fat} = \sqrt{\tan\theta} \leq 1$$



4.6 VERIFICATION OF CONCRETE TO SHEAR / VERIFICAREA BETONULUI LA FORFECARE

Compression struts of members subjected to shear resist to fatigue if the following conditions are fulfilled:

$$\frac{\sigma_{c,max}}{\nu\, f_{cd,fat}} \leq 0{,}5 + 0{,}45\frac{\sigma_{c,min}}{\nu\, f_{cd,fat}}$$

$$\leq 0{,}9 \quad \text{for } f_{ck} \leq 50\ MPa$$

$$\leq 0{,}8 \quad \text{for } f_{ck} > 50\ MPa$$

where

$$\sigma_{c,max} = \frac{V_{Ed,f}}{b_w z}(ctg\theta_{fat} + tg\theta_{fat})$$

$$\sigma_{c,min} = \frac{V_{Ed,min}}{b_w z}(ctg\theta_{fat} + tg\theta_{fat})$$

$$\nu = 0{,}6\left[1 - \frac{f_{ck}}{250}\right]$$

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THANK YOU FOR YOUR ATTENTION!!!