CRACKING AND CRACK CONTROL

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1. CAUSES OF CRACKING

2. GENERAL CONSIDERATIONS ABOUT CRACK CONTROL

3. CRACK CONTROL BY CALCULATION

4. CRACK CONTROL WITHOUT CALCULATION

5. MINIMUM REINFORCEMENT AREAS

CAUSES OF CRACKING

Cracking of reinforced concrete elements → an unavoidable phenomenon

⇒ the inability of concrete to take tensile stresses

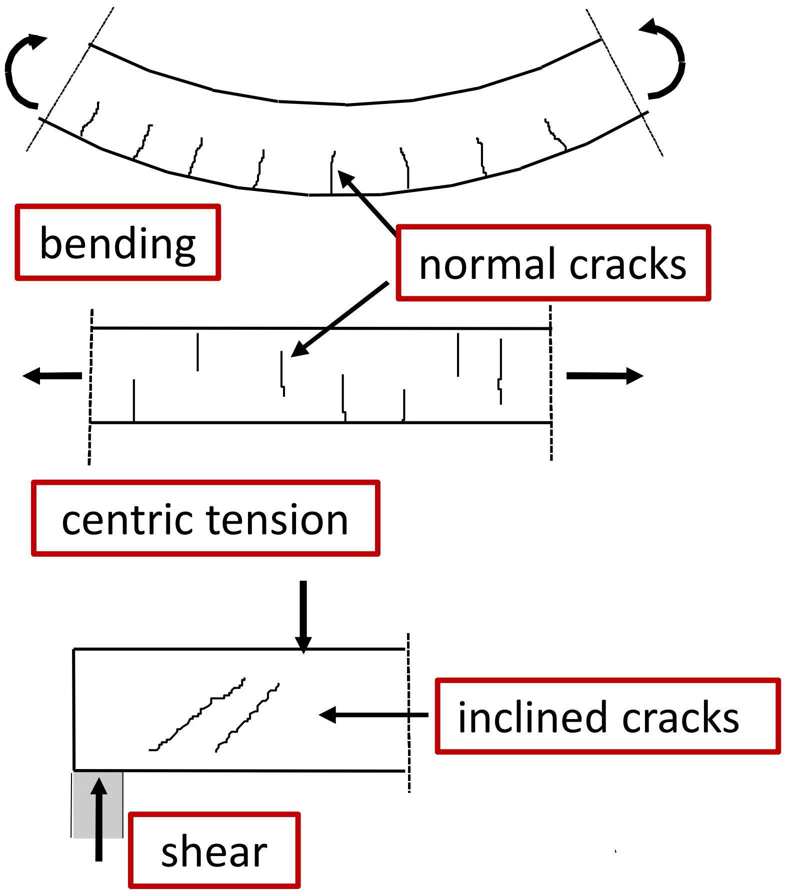
Cracks could be:

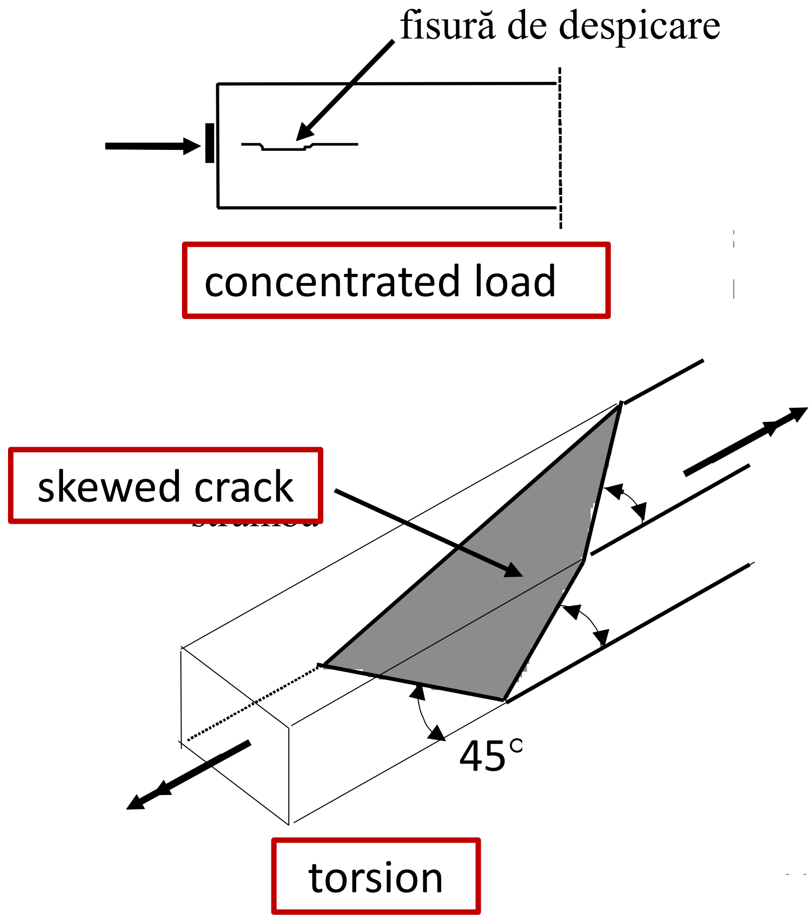
- **Extrinsic =** produced be external causes
  - loads
  - imposed deformations

- **Intrinsic =** generated in the interior of concrete
  - restrained **shrinkage** of concrete
  - variation of **temperature**
  - **plastic settlement** of fresh concrete
  - expansive products of **corrosion**
  - **freeze-thaw** repeatedly actions
  - **irregularities** in the execution process

1. Causes of cracking / Cauzele fisurării

FISURI PRODUSE DE SOLICITĂRI





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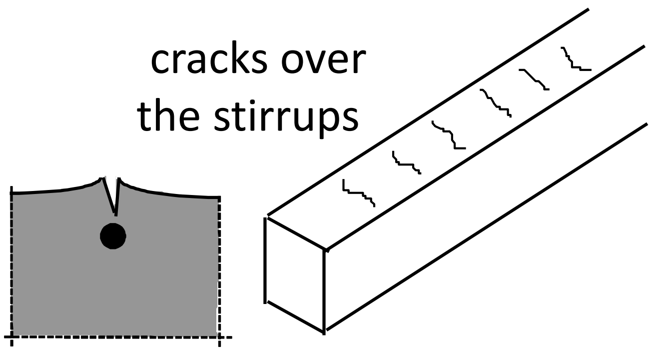
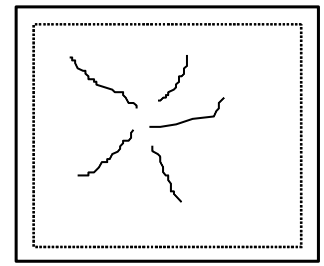
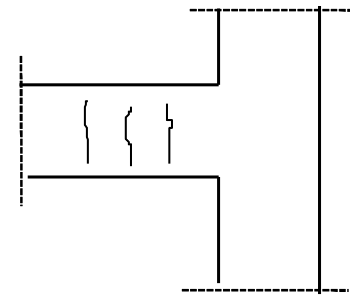
FISURI CU CARACTER ÎNTÂMPLĂTOR



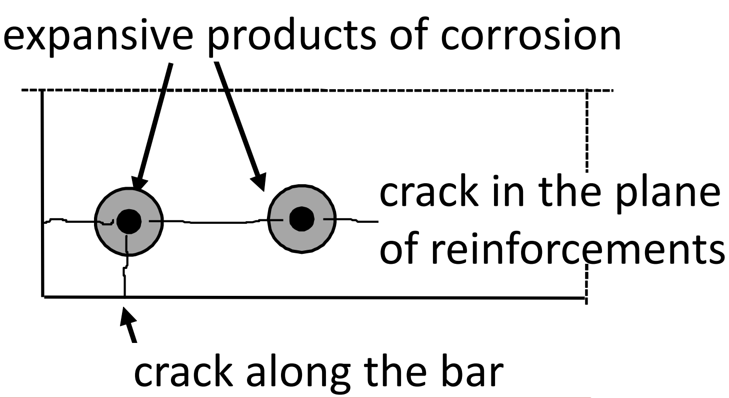
plastic settlement of fresh concrete



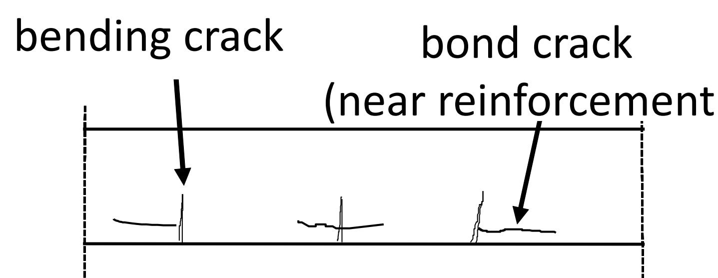
Scaffolding displacement of the slab formwork



Scaffolding displacement of the beam formwork



reinforcement corrosion



high bond stresses

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1. Causes of cracking / Cauzele fisurării

CRACKS APPEARED BEFORE THE CONCRETE HARDENING		Tip
Phenomena due to fresh concrete behaviour	Plastic shrinkage Plastic settlement	Intrinsic Intrinsic
Phenomena due to execution process	Movement of the scaffoldings and/or formworks	Extrinsic Extrinsic
Thermal effects	Early frost	Extrinsic
CRACKS APPEARED AFTER THE CONCRETE HARDENING		
Physical phenomena	Contractile aggregates Shrinkage Microcracking due to use	Intrinsic Intrinsic Extrinsic
Chemical reactions	Reinforcement corrosion Alkali – aggregate reactions	Intrinsic Intrinsic
Thermal effects	Freeze - thaw repeatedly Thermal variation of the environment Inner thermal variation during the hardening	Extrinsic Extrinsic Intrinsic
Structural causes	Actions with design intensity Accidental overload Concrete creep	Extrinsic Extrinsic I & E

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2. General considerations about crack control / Considerații generale despre controlul fisurării

Cracking process: Phase 1 → **formation of cracks**
Phase 2 → **opening of cracks**

Crack width is a function of the number of cracks per unit length of the element, so **depends on the distance between the cracks**.

The need for crack control

- Appearance and proper functioning of the elements
- Water and gas tightness
- Corrosion protection

⇒ **Exigencies/Conditions that define acceptable limits for crack width**

2. General considerations about crack control / Considerații generale despre controlul fisurării

Crack width depends on:

- reinforcing coefficient
- rebar diameter and bond properties
- magnitude of the reinforcement stress
- load character: static or dynamic
- bar spacing
- concrete cover
- concrete quality

Checking of crack width is done in the 2nd stage (service stage), taking into account the resulting stresses form quasi-permanent combination of actions!

$$G + \psi_2 Q_k$$

ψ_2 - reversible SLS, long term effects

2. General considerations about crack control / Considerații generale despre controlul fisurării

Table A1.1 - Recommended values of ψ factors for buildings

Action	ψ_0	ψ_1	ψ_2
Imposed loads in buildings, category (see EN 1991-1-1)			
Category A : domestic, residential areas	0,7	0,5	0,3
Category B : office areas	0,7	0,5	0,3
Category C : congregation areas	0,7	0,7	0,6
Category D : shopping areas	0,7	0,7	0,6
Category E : storage areas	1,0	0,9	0,8
Category F : traffic area, vehicle weight ≤ 30kN	0,7	0,7	0,6
Category G : traffic area, 30kN < vehicle weight ≤ 160kN	0,7	0,5	0,3
Category H : roofs	0	0	0
Snow loads on buildings (see EN 1991-1-3)*			
Finland, Iceland, Norway, Sweden	0,70	0,50	0,20
Remainder of CEN Member States, for sites located at altitude H > 1000 m a.s.l.	0,70	0,50	0,20
Remainder of CEN Member States, for sites located at altitude H ≤ 1000 m a.s.l.	0,50	0,20	0
Wind loads on buildings (see EN 1991-1-4)	0,6	0,2	0
Temperature (non-fire) in buildings (see EN 1991-1-5)	0,6	0,5	0
NOTE The ψ values may be set by the National annex. * For countries not mentioned below, see relevant local conditions.			

EN 1990:2002

2. General considerations about crack control / Considerații generale despre controlul fisurării

Tabelul 7.1 Valori recomandate pentru factorii de grupare (combinare) a acțiunilor variabile la clădiri şi structuri

Acțiunea	Factori de grupare		
	ψ_0	ψ_1	ψ_2
Acțiuni din exploatare provenind din funcțiunea clădirii			
- Rezidentială	0,7	0,5	0,3
- Birouri	0,7	0,5	0,3
- Întrunire/Adunare	0,7	0,7	0,6
- Spații comerciale	0,7	0,7	0,6
- Spații de depozitare	1,0	0,9	0,8
- Acoperişuri	0,7	0	0
Acțiuni din trafic			
- Greutatea vehiculelor <30kN	0,7	0,7	0,6
- Greutatea vehiculelor 30 ÷ 160kN	0,7	0,5	0,3
Acțiuni din zăpadă	0,7	0,5	0,4
Acțiuni din vânt	0,7	0,2	0
Acțiuni din variații de temperatură	0,6	0,5	0

unde semnificațiile simbolurilor sunt următoarele:

ψ_0 – Factor pentru valoarea de grupare a acțiunii variabile
ψ_1 – Factor pentru valoarea frecventă a acțiunii variabile
ψ_2 – Factor pentru valoarea cvasipermanentă a acțiunii variabile.

(CR 0-2012)

2. General considerations about crack control / Considerații generale despre controlul fisurării

The limit value for crack width w_{max} is determined according to the function and nature of the structure.

In the absence of specific requirements, the durability and proper appearance of the elements will be ensured.

Table 7.1N Recommended values of w_{max} (mm)

Exposure Class	Reinforced members and prestressed members with unbonded tendons	~~Prestressed~~ members with bonded tendons
	Quasi-permanent load combination	Frequent load combination
X0, XC1	0,4[1]	0,2
XC2, XC3, XC4	0,3	0,2[2]
XD1, XD2, XS1, XS2, XS3		Decompression

Note 1: For X0, XC1 exposure classes, crack width has no influence on durability and this limit is set to guarantee acceptable appearance. In the absence of appearance conditions this limit may be relaxed.
Note 2: For these exposure classes, in addition, decompression should be checked under the quasi-permanent combination of loads.

(EN 1992-1-1:2004)

Crack control:

1) calculation of crack width and comparison with recommended values

$$w_k \leq w_{max}$$

2) limitation of bars diameter or the distance between them.

Whichever is the control procedure and the reinforcement quantity resulted from ULS, a minimum amount of bonded reinforcement is required to control cracking in areas where tension is expected.

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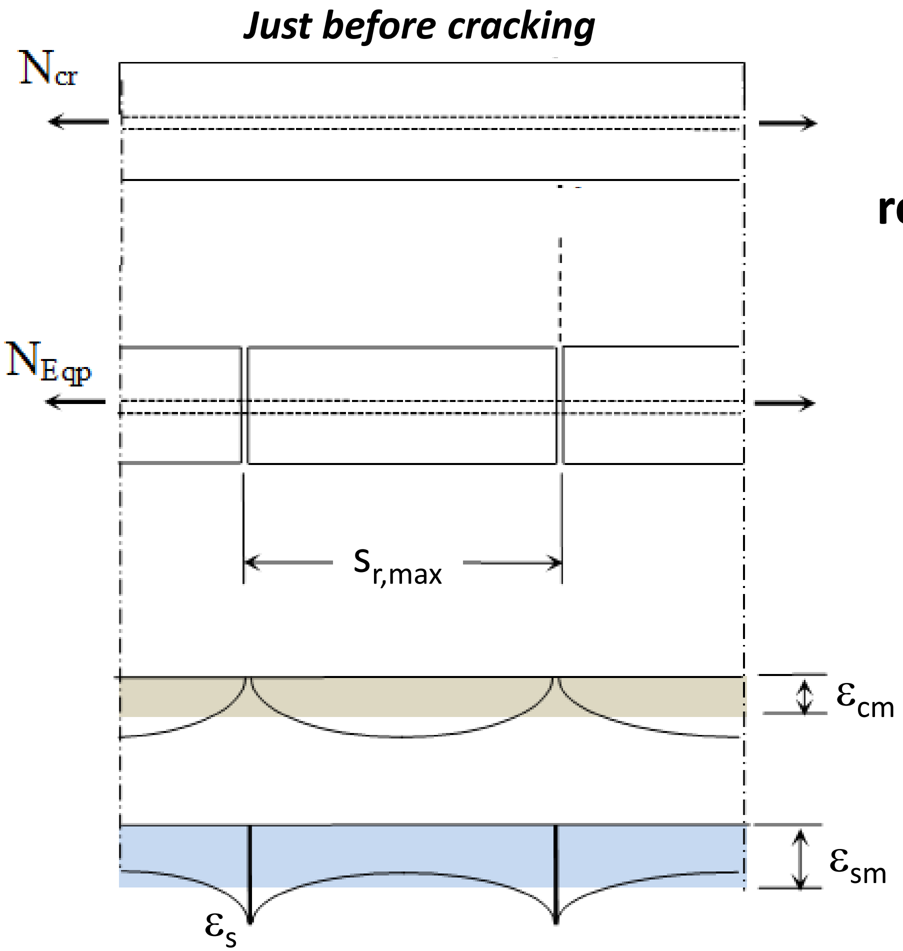
3. Crack control by calculation / Controlul fisurării prin calcule

Distance between the cracks

Crack width (w_k) **is a function of** number of cracks per unit length of the element, so **<u>depends on the distance between the cracks</u>** ($s_{r,max}$) .

$$\varepsilon = \frac{\Delta l}{l}$$



On the length $s_{r,max}$

rebar elongation = concrete elongation + w_k

$$\varepsilon_{sm} s_{r,max} = \varepsilon_{cm}(\underbrace{s_{r,max}}_{\geq 100\text{ mm}} - \underbrace{w_k}_{< 0{,}1\text{ mm}}) + w_k$$

$$w_k = (\varepsilon_{sm} - \varepsilon_{cm}) s_{r,max}$$

Contribution of tension concrete

≡

tension stiffening

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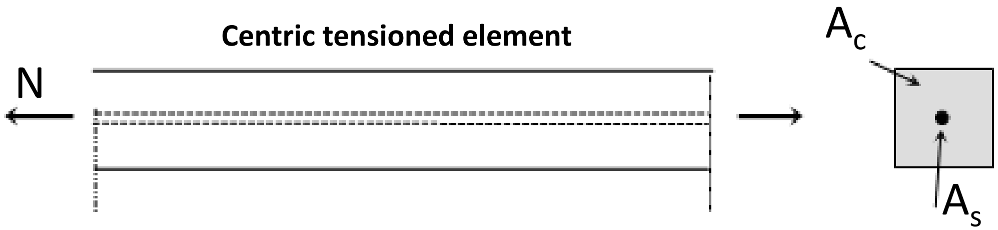
3. Crack control by calculation / Controlul fisurării prin calcule

Distance between the cracks



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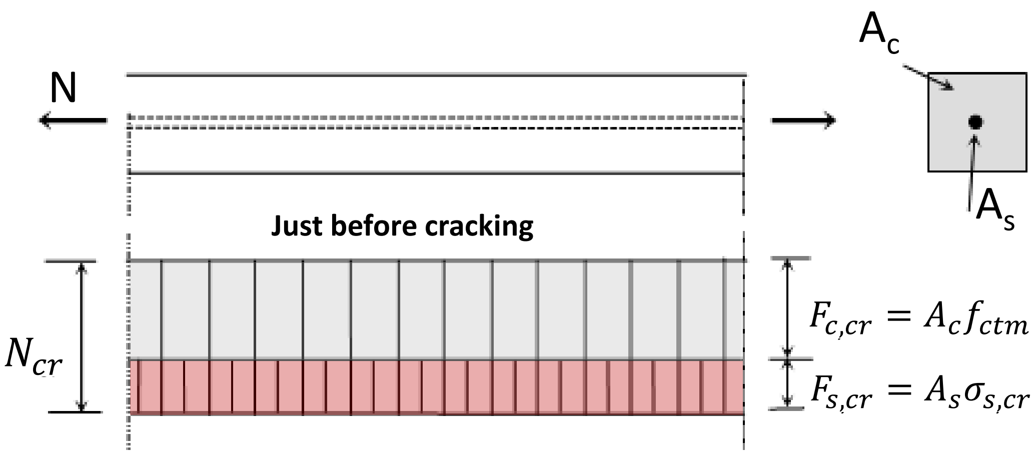
3. Crack control by calculation / Controlul fisurării prin calcule

Distance between the cracks



Limit of stage I.

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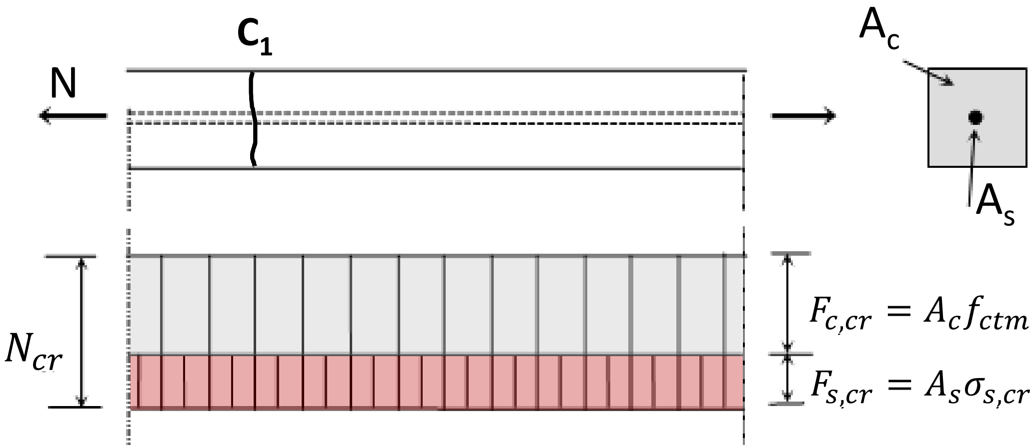
3. Crack control by calculation / Controlul fisurării prin calcule

Distance between the cracks



Limit of stage I.

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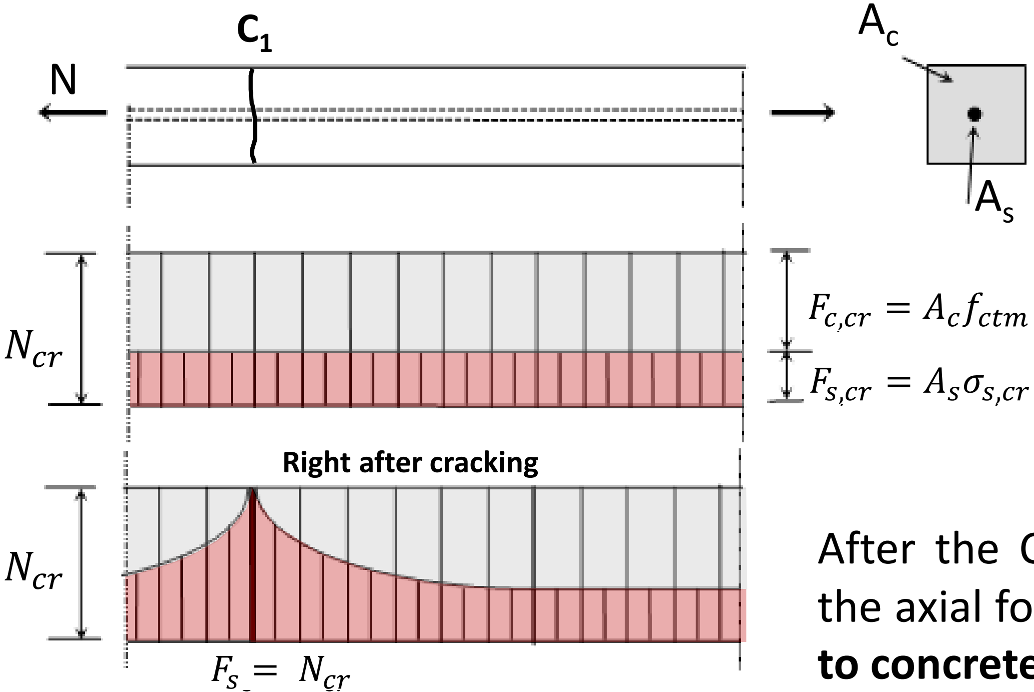

Limit of stage I.

After the C_1 crack formed, reinforcement takes all the axial force → **force transfer from reinforcement to concrete**

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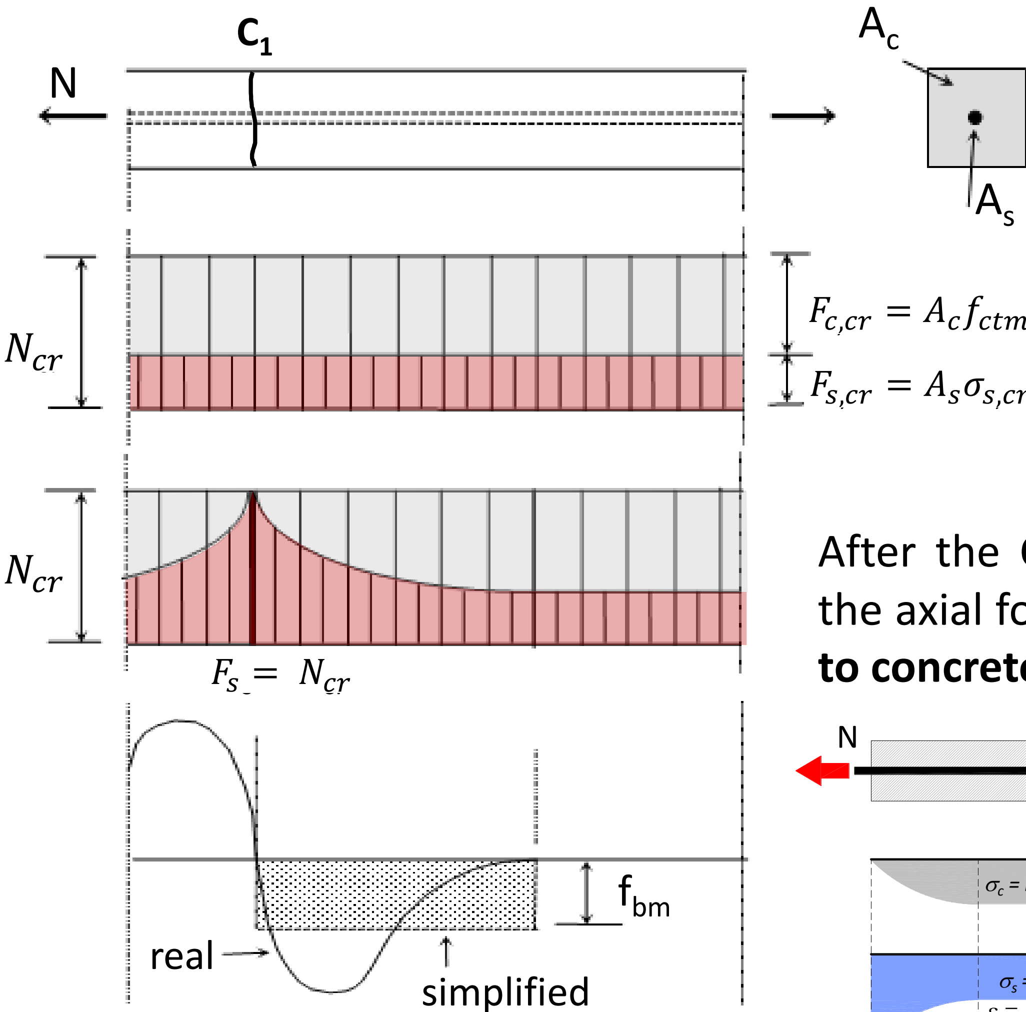
3. Crack control by calculation / Controlul fisurării prin calcule

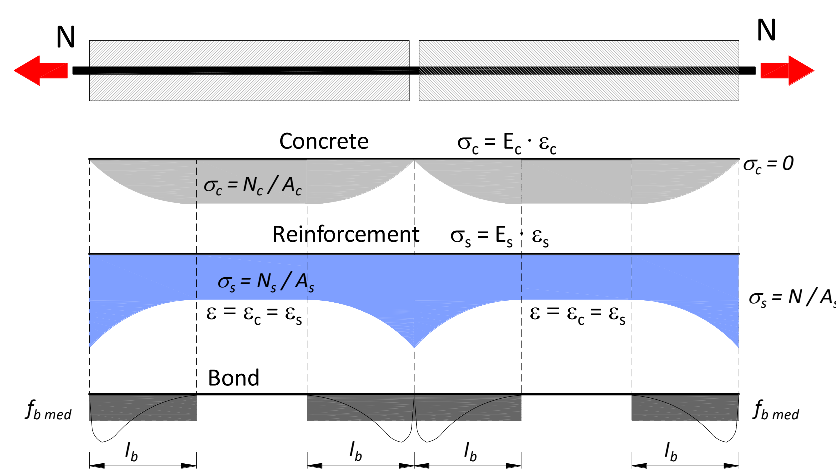
Distance between the cracks



Bond stress distribution

Limit of stage I.

After the C_1 crack formed, reinforcement takes all the axial force → **force transfer from reinforcement to concrete by bond**



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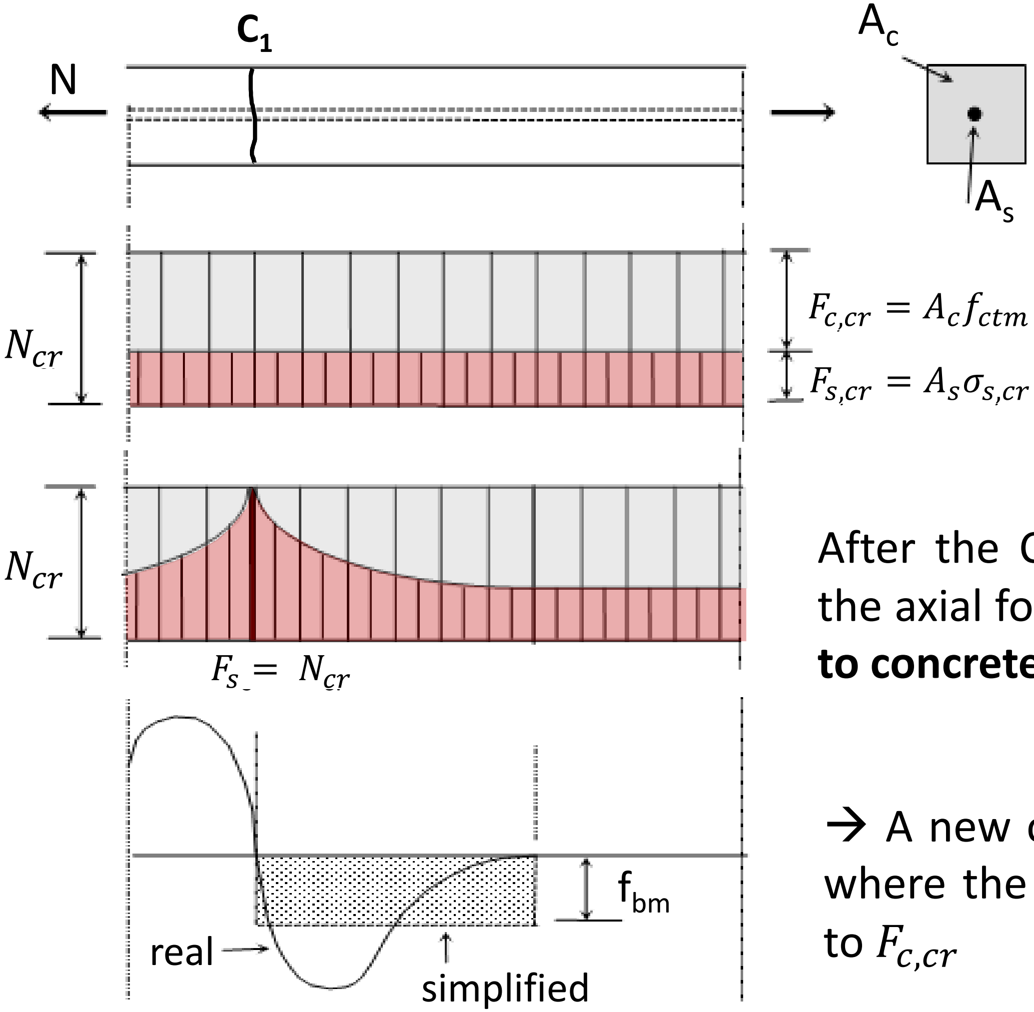
3. Crack control by calculation / Controlul fisurării prin calcule

Distance between the cracks



Limit of stage I.

After the C_1 crack formed, reinforcement takes all the axial force → **force transfer from reinforcement to concrete by bond**

→ A new crack is possible to appear in the section where the tensile force in concrete becomes equal to $F_{c,cr}$

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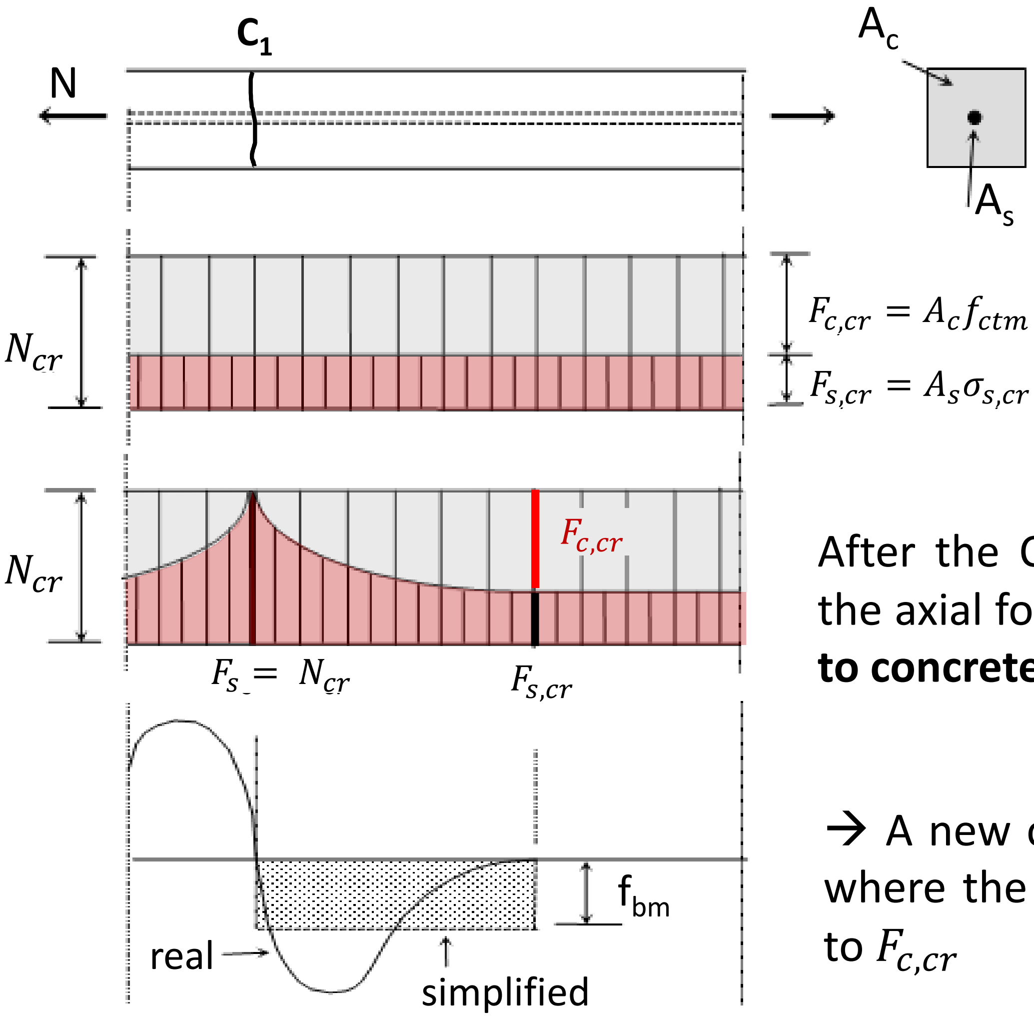
3. Crack control by calculation / Controlul fisurării prin calcule

Distance between the cracks



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(Prof. Clipii)

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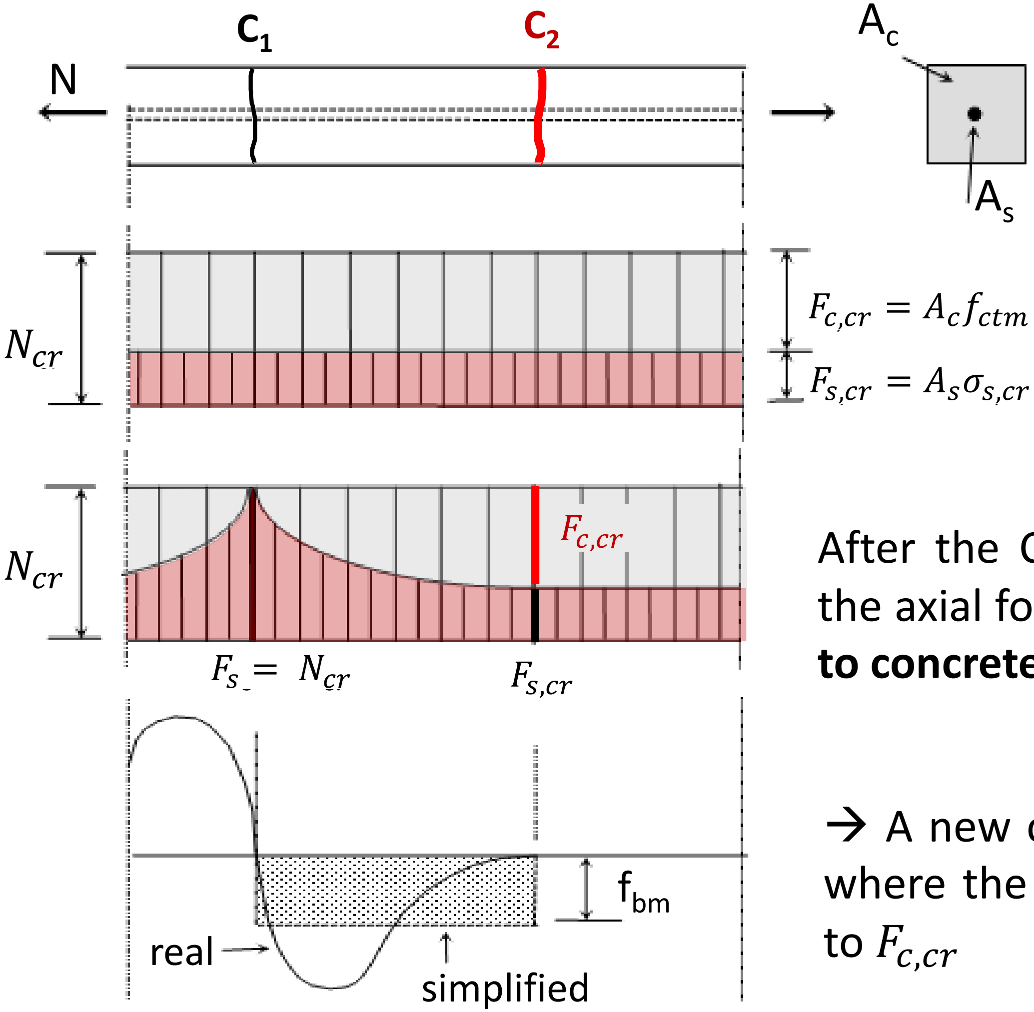

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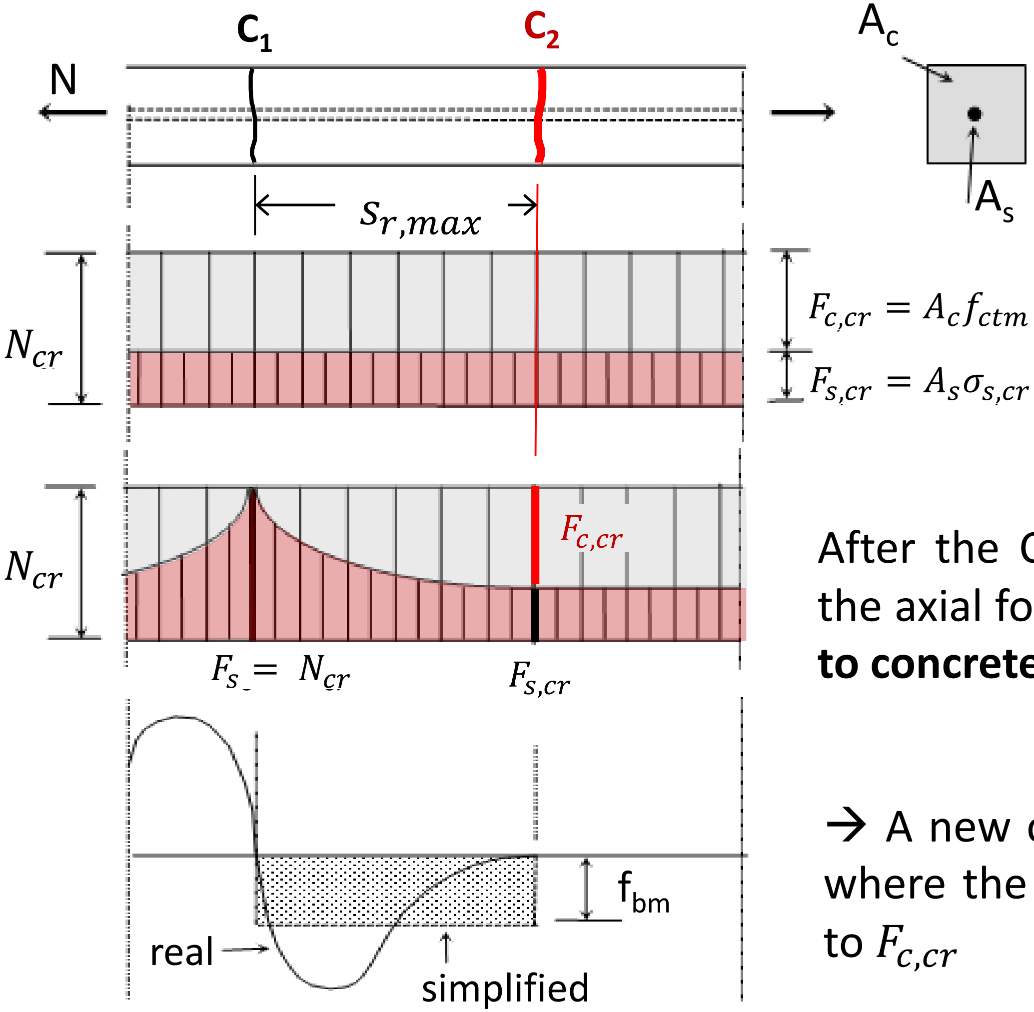
(Prof. Clipii)

3. Crack control by calculation / Controlul fisurării prin calcule

Distance between the cracks



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After the C_1 crack formed, reinforcement takes all the axial force → **force transfer from reinforcement to concrete by bond**

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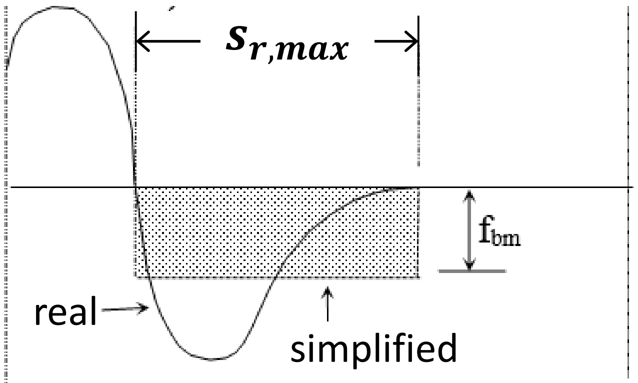
$s_{r,max}$ - maximum crack spacing

(Prof. Clipii)

3. Crack control by calculation / Controlul fisurării prin calcule

Distance between the cracks



d) Bond stress distribution

- On the length $s_{r,max}$ there is transfer of the force $F_{c,cr}$ from reinforcement to concrete by the bond force F_b

- Real distribution of bond stress is non-linear, but for simplification of calculus can be adopted a rectangular distribution

$$F_b = F_{c,cr}$$

$$u s_{r,max} f_{bm} = A_c f_{ctm} \quad \Rightarrow \quad s_{r,max} = \frac{A_c f_{ctm}}{u f_{bm}}$$

where $u = \pi\phi$ - rebar perimeter

$$\rho = \frac{A_s}{A_c} \quad \Rightarrow \quad A_c = \frac{A_s}{\rho} = \frac{\pi\phi^2}{4\rho} \quad \Rightarrow \quad s_{r,max} = 0{,}25 \frac{f_{ctm}}{f_{bm}} \frac{\phi}{\rho}$$

$\Rightarrow$ Diameter ϕ ↘
Reinforcing coefficient ρ ↗
bond ↗

$\Rightarrow s_{r,max}$ ↘ $\Rightarrow$ w_k ↘

$w_k = (\varepsilon_{sm} - \varepsilon_{cm}) s_{r,max}$ (Prof. Clipii)

In EC2: crack spacing depends on the distance between bars

a) Distance between bars $\leq 5(c+\phi/2)$ – usual situation

$$s_{r,max} = 3,4c + 0,425 k_1 k_2 \frac{\phi}{\rho_{p,eff}}$$

where

ϕ - bar diameter
- where a mixture of bar diameters is used in a section, an equivalent diameter: $\phi_{ech} = \sum n\phi^2 / \sum n\phi$

c - concrete cover to the longitudinal reinforcement

k_1 - coefficient which takes account of the bond properties of the reinforcement:
= 0,8 for high bond bars
= 1,6 for plain bars

k_2 coefficient which takes account of the distribution of strain:
= 0,5 for bending
= 1,0 for pure tension
$= (\varepsilon_1 + \varepsilon_2)/2\varepsilon_1$ for cases of eccentric tension, in which ε_1 is the greater and ε_2 the lesser tensile strain at the boundaries of the section considered, assessed on the basis of a cracked section

$\rho_{p,eff} = A_s / A_{c,eff}$

$A_{c,eff}$ effective area of concrete in tension surrounding the reinforcement of depth $h_{c,ef}$

$h_{c,ef} = \min[2{,}5(h-d); (h-x)/3\,; h/2]$

(Prof. Clipii)

In EC2: crack spacing depends on the distance between bars

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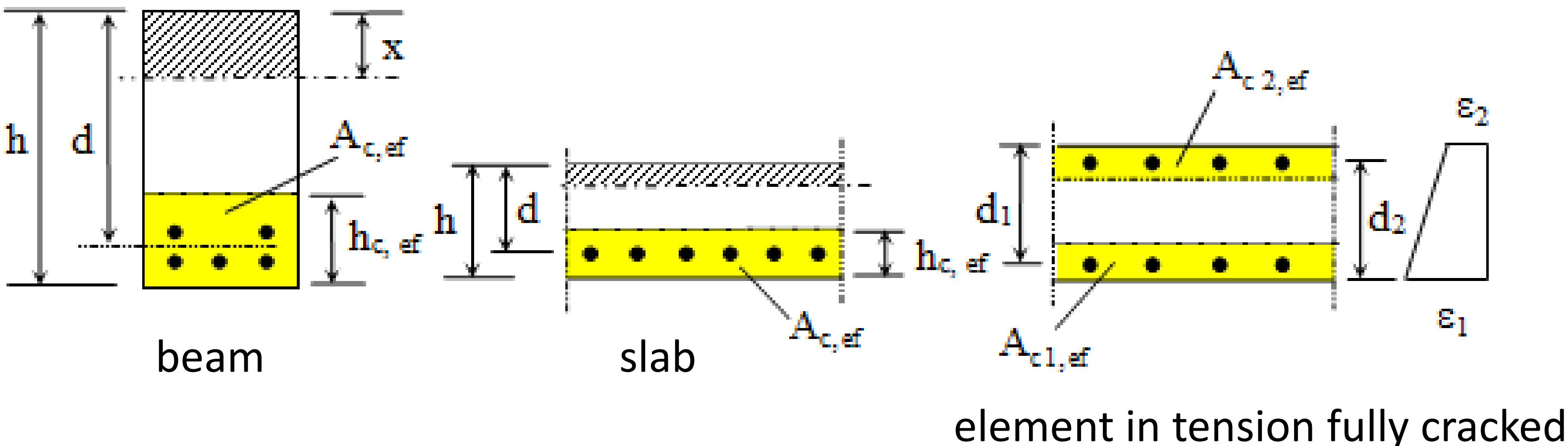


$$h_{c,ef} = min \begin{cases} 2.5(h-d) \\ (h-x)/3 \\ h/2 \end{cases}$$

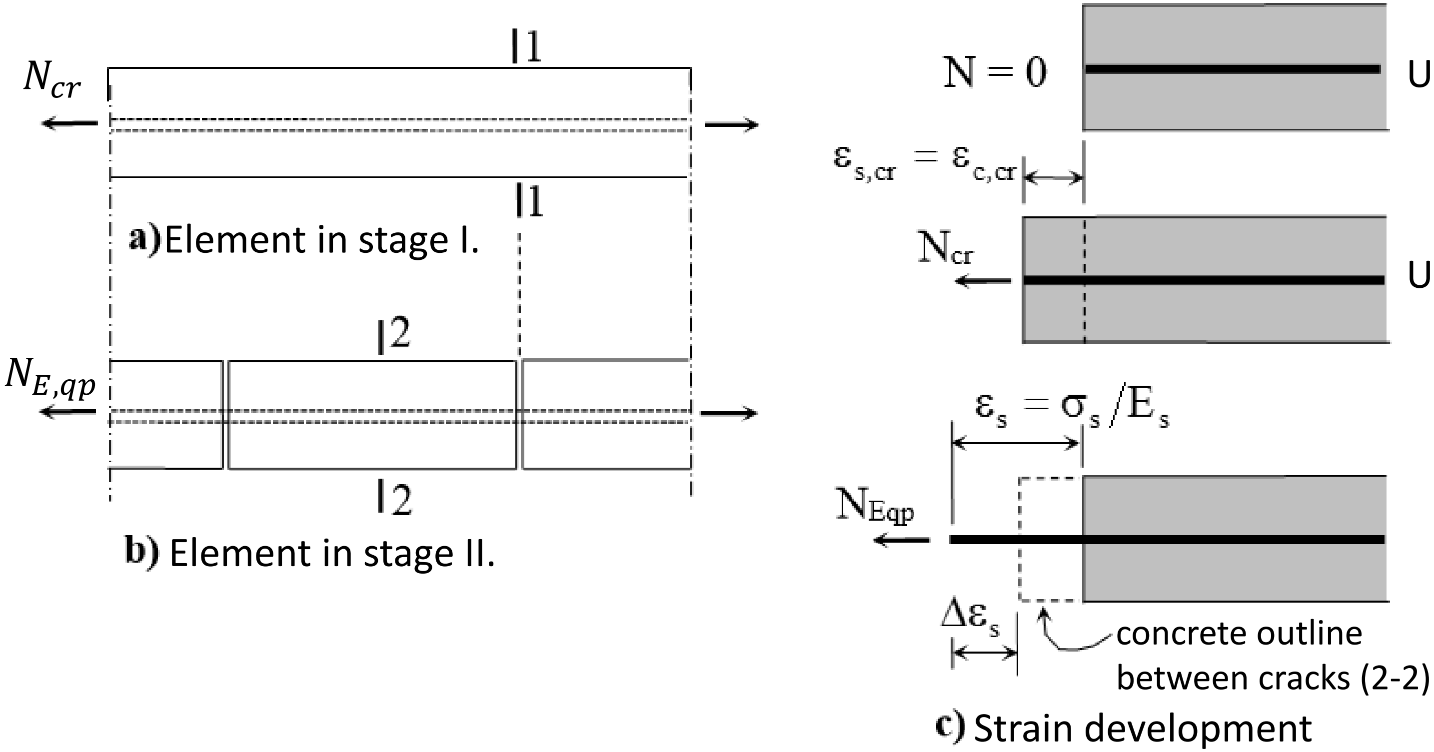
(Prof. Clipii)

In EC2: crack spacing depends on the distance between bars

b) Distance between bars $> 5(c + \phi/2)$ – slabs, massive elements

$$s_{r,max} = 1,3(h - x)$$

Crack width calculation



Capacity at cracking is given by the contribution of both materials :

$$N_{cr} = A_c f_{ctm} + A_s \sigma_{s,cr}$$

(Prof. Clipii)

3. Crack control by calculation / Controlul fisurării prin calcule

Crack width calculation

At the level of reinforcement, concrete and steel have identical strain

$$\varepsilon_s = \varepsilon_c \;\rightarrow\; \sigma_s/E_s = \sigma_c/E_c \;\rightarrow\; \sigma_s = \sigma_c(E_s/E_c) \;\rightarrow\; \sigma_s = \alpha_e\sigma_c$$

$\alpha_e = E_s/E_c$ coefficient of equivalence

$$\rightarrow \quad N_{cr} = A_c f_{ctm} + A_s\sigma_{s,cr} = A_c f_{ctm}\left(1 + \alpha_e \frac{A_s}{A_c}\right) = A_c f_{ctm}(1 + \rho\alpha_e)$$

Just before cracking

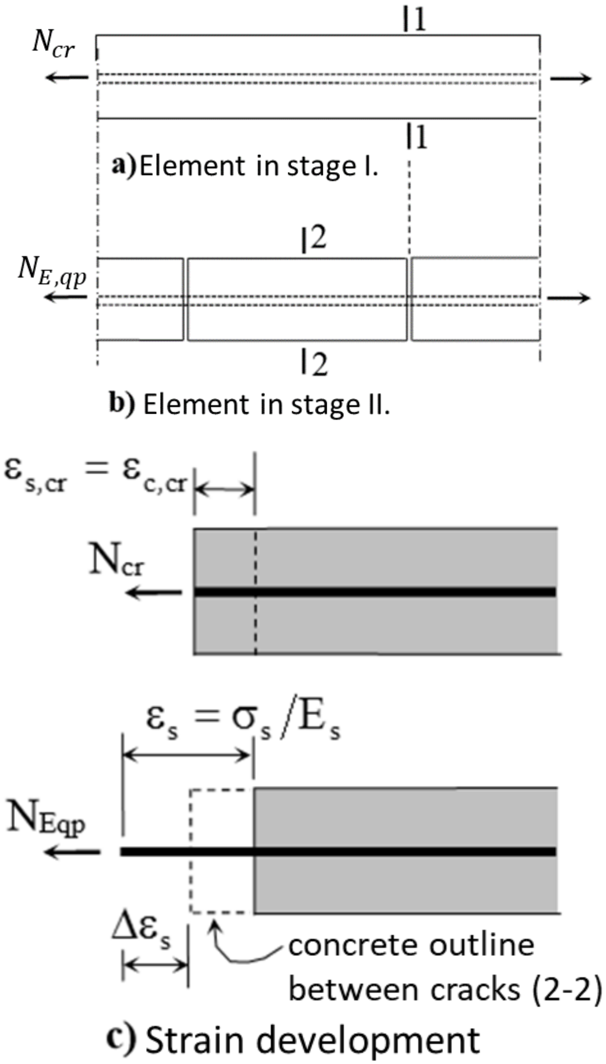
$$\varepsilon_{s,cr} = \varepsilon_{c,cr} = \frac{N_{cr}}{E_s A_s} = \frac{A_c f_{ctm}(1 + \rho\alpha_e)}{E_s A_s}$$

3. Crack control by calculation / Controlul fisurării prin calcule

Crack width calculation

Crack width is determined by the **increasing (Δ) of the strain** in reinforcement from

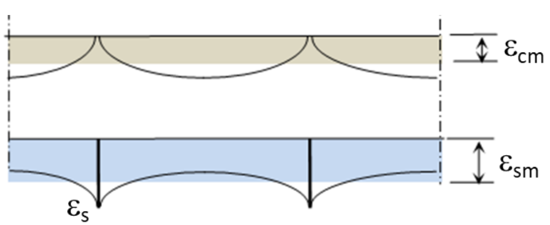
$\varepsilon_{s,cr} = \varepsilon_{c,cr}$ up to the value of $\varepsilon_s = \sigma_s / E_s$



$$\Delta\varepsilon_s = \varepsilon_s - \varepsilon_{s,cr} = \boldsymbol{\varepsilon_s - \varepsilon_{c,cr}} = \frac{\sigma_s}{E_s} - \frac{A_c f_{ctm}(1 + \rho\alpha_e)}{E_s A_s}$$

$$w_k = s_{r,max}\Delta\varepsilon_s = s_{r,max}(\varepsilon_s - \varepsilon_{c,cr})$$

Formula in EC2: $\boldsymbol{w_k = s_{r,max}(\varepsilon_{sm} - \varepsilon_{cm})}$



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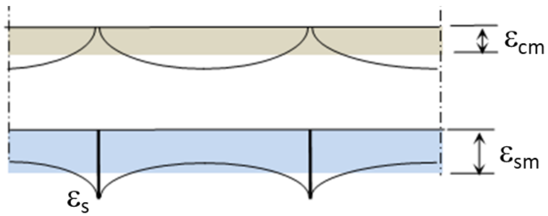
Formula in EC2



$$\boldsymbol{w_k = s_{r,max}(\varepsilon_{sm} - \varepsilon_{cm})}$$

where

ε_{sm} - the mean strain in the reinforcement under the relevant combination of loads, including the effect of imposed deformations and taking into account the effects of tension stiffening.

ε_{cm} - the mean strain in the concrete between cracks

$\varepsilon_{sm} - \varepsilon_{cm}$ may be calculated from the expression

$$\varepsilon_{sm} - \varepsilon_{cm} = \frac{\sigma_s - k_t \dfrac{f_{ct,eff}}{\rho_{p,eff}}\left(1 + \alpha_e \rho_{p,eff}\right)}{E_s} \geq 0.6\frac{\sigma_s}{E_s}$$

σ_s - stress in the tension reinforcement assuming a cracked section

$\sigma_s = \alpha_e \frac{M}{I_{II}}(d - x)$ Navier's formula applied for bent RC section

k_t - factor dependent on the duration of the load
= 0,6 for short term loading
= 0,4 for long term loading

$\rho_{p,eff} = A_s / A_{c,eff}$

$f_{ct,eff}$ for crack width calculation and contribution of tensile concrete $f_{ct,eff} = f_{ctm}$

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CONTROL OF CRACKING WITHOUT DIRECT CALCULATION

For reinforced concrete slabs subjected to bending without significant axial tension, specific measures to control cracking are not necessary where the overall depth does not exceed 200 mm and the detailing provisions have been applied.

Where the minimum amount of reinforcement is provided, crack widths are unlikely to be excessive if:

- for cracking caused dominantly by restraint, the bar sizes given in Table 7.2N are not exceeded where the steel stress (σ_s) is the value obtained immediately after cracking (may be assumed f_{yk}).

- for cracks caused mainly by loading, either the provisions of Table 7.2N or the provisions of Table 7.3N are complied with. The steel stress (σ_s) should be calculated on the basis of a cracked section under the quasi permanent combination of actions.

4. Crack control without calculation / Controlul fisurării fără calcule

Table 7.2N Maximum bar diameters ϕ^*_s for crack control[1]

Steel stress[2] [MPa]	Maximum bar size [mm] w_k= 0,4 mm	w_k= 0,3 mm	w_k= 0,2 mm
160	40	32	25
200	32	25	16
240	20	16	12
280	16	12	8
320	12	10	6
360	10	8	5
400	8	6	4
450	6	5	-

Notes: 1. The values in the table are based on the following assumptions:
c = 25mm; $f_{ct,eff}$ = 2,9MPa; h_{cr} = 0,5; $(h-d) = 0,1h$; k_1 = 0,8; k_2 = 0,5; k_c = 0,4; k = 1,0; k_t = 0,4 and k' = 1,0

2. Under the relevant combinations of actions

4. Crack control without calculation / Controlul fisurării fără calcule

Table 7.3N Maximum bar spacing for crack control[1]

Steel stress[2] [MPa]	Maximum bar spacing [mm] w_k=0,4 mm	w_k=0,3 mm	w_k=0,2 mm
160	300	300	200
200	300	250	150
240	250	200	100
280	200	150	50
320	150	100	-
360	100	50	-

4. Crack control without calculation / Controlul fisurării fără calcule

Steel stress σ_s (MPa)	**Maximum bar size** (mm) for w_k			**Maximum bar spacing** (mm) for w_k		
	0,4 mm	0,3 mm	0,2 mm	0,4 mm	0,3 mm	0,2 mm
160	40	32	25	300	300	200
200	32	25	16	300	250	150
240	20	16	12	250	200	100
280	16	12	8	200	150	50
320	12	10	6	150	100	-
360	10	8	5	100	50	-
400	8	6	4	-	-	-
450	6	5	-	-	-	-

Bending (at least part of section in compression):

$$\phi_s = \phi^*_s \, (f_{ct,eff}/2,9) \, \frac{k_c h_{cr}}{2\,(h-d)} \qquad (7.6N)$$

Tension (uniform axial tension)

$$\phi_s = \phi^*_s(f_{ct,eff}/2,9)h_{cr}/(8(h-d)) \qquad (7.7N)$$

where:

- ϕ_s is the adjusted maximum bar diameter
- ϕ^*_s is the maximum bar size given in the Table 7.2N
- h is the overall depth of the section
- h_{cr} is the depth of the tensile zone immediately prior to cracking, considering the characteristic values of prestress and axial forces under the quasi-permanent combination of actions
- d is the effective depth to the centroid of the outer layer of reinforcement

(Prof. Clipii)

1. CAUSES OF CRACKING

2. GENERAL CONSIDERATIONS ABOUT CRACK CONTROL

3. CRACK CONTROL BY CALCULATION

4. CRACK CONTROL WITHOUT CALCULATION

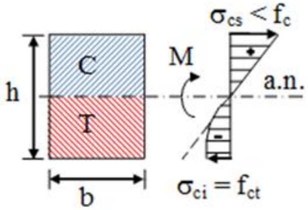
5. MINIMUM REINFORCEMENT AREAS

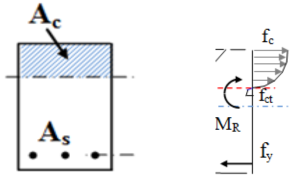
5. Minimum reinforcement areas / Arii de armături minime

If crack control is required, a minimum amount of bonded reinforcement is required to control cracking in areas where tension is expected.

→ this amount may be estimated from equilibrium between the tensile force in concrete just before cracking and the tensile force in reinforcement at yielding (or at a lower stress if necessary to limit the crack width).

$$A_s f_{yk} \geq A_c f_{ctm}$$





minimum reinforcement should be determined for the individual parts of the section (webs, flanges)

$$A_{s,min} = k_c k f_{ct,ef} A_{ct} / \sigma_s$$

A_{ct} is the area of concrete within tensile zone. The tensile zone is that part of the section which is calculated to be in tension just before formation of the first crack

σ_s is the absolute value of the maximum stress permitted in the reinforcement immediately after formation of the crack. This may be taken as the yield strength of the reinforcement, f_{yk}. A lower value may, however, be needed to satisfy the crack width limits according to the maximum bar size or spacing

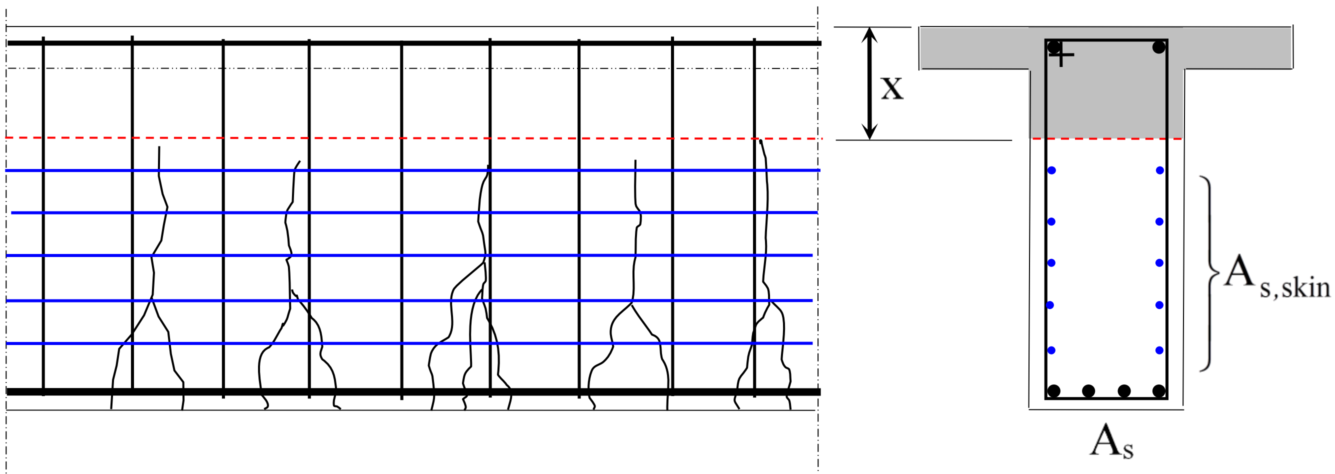
$f_{ct,ef} = f_{ctm}$ mean value of the tensile strength of the concrete effective at the time when the cracks may first be expected to occur

k is the coefficient which allows for the effect of non-uniform self-equilibrating stresses

k_c a coefficient which takes account of the stress distribution within the section immediately prior to cracking and of the change of the lever arm

5. Minimum reinforcement areas / Arii de armături minime

In the case of **high beams**, where the reinforcements resulted from bending moment are concentrated only on a small part of the height (e.g. bottom), there is an **increase in the distance between the cracks**, which leads to an **increase in the crack width**



h ≥ 1,0 m

In order to control the cracks on the side faces of the beams, additional reinforcements must be provided on the side faces inside the stirrups, uniform distributed between the main reinforcements and the neutral axis

$$A_{s,skin} \geq 0{,}5 k_c k f_{ct,ef} A_{ct}/f_{yk}$$

Distances between suplimentary bars and their diameter could be established with tabel 7.2N

THANK YOU FOR YOUR ATTENTION !!!

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