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Transfer of prestress

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Cerib | France

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HOLLOWCORE SLAB and FLOOR DESIGN

Transfer of Prestressing
by Matthieu SCALLIET

IPHA Technical Seminar 25-26 October 2017

Tendon

- The main tendons of hollow core slabs are composed of steel wires (1) or strands (2):

(1)

(2)

- This tendon is positioned underneath the vertical webs, where the section of concrete allows optimum covering of the steel

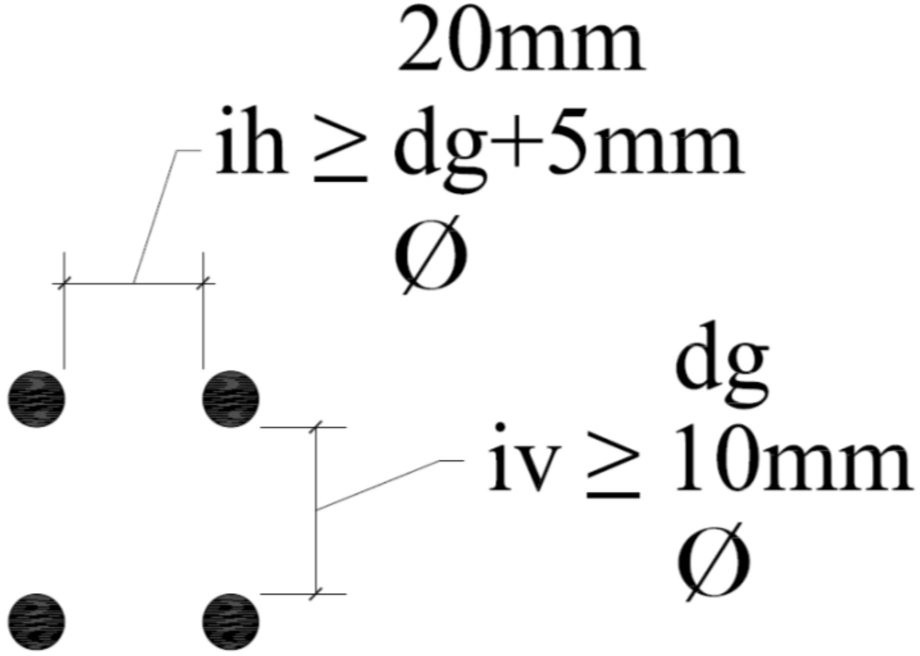
Concrete cover

- The minimum concrete cover c_{min} to the nearest concrete surface and the nearest edge of a core shall be at least:
  - ➢ Only with respect to the exposed face, in accordance with EN 1992-1-1 for durability ($c_{min,dur}$)
  - ➢ For preventing longitudinal cracking due to bursting and splitting
    - ❑ $C_{min,b} = 1{,}5\ Ø$ if the distance between centres of the strands is $\geq 3\ Ø$
    - ❑ $C_{min,b} = 2{,}5\ Ø$ if the distance between centres of the strands is $< 2{,}5\ Ø$

  Where Ø is the strand or wire diameter

Clear spacing

- The clear spacing between prestressing strands shall be al least:



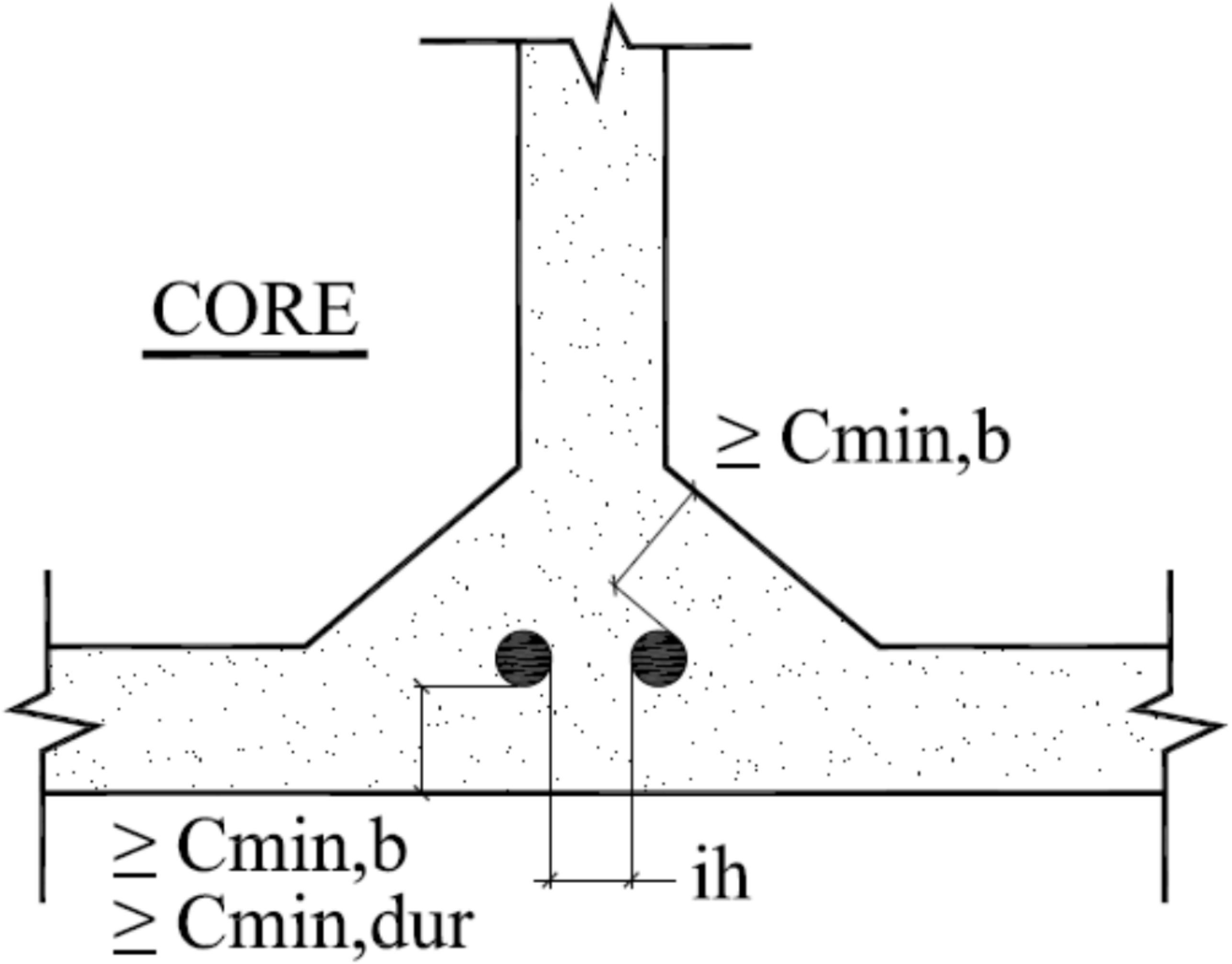
$$ih \geq \begin{matrix} 20\text{mm} \\ dg+5\text{mm} \\ \varnothing \end{matrix}$$

$$iv \geq \begin{matrix} dg \\ 10\text{mm} \\ \varnothing \end{matrix}$$

- ➢ Horizontally **i_h** :
- ➢ Vertically **i_v** :

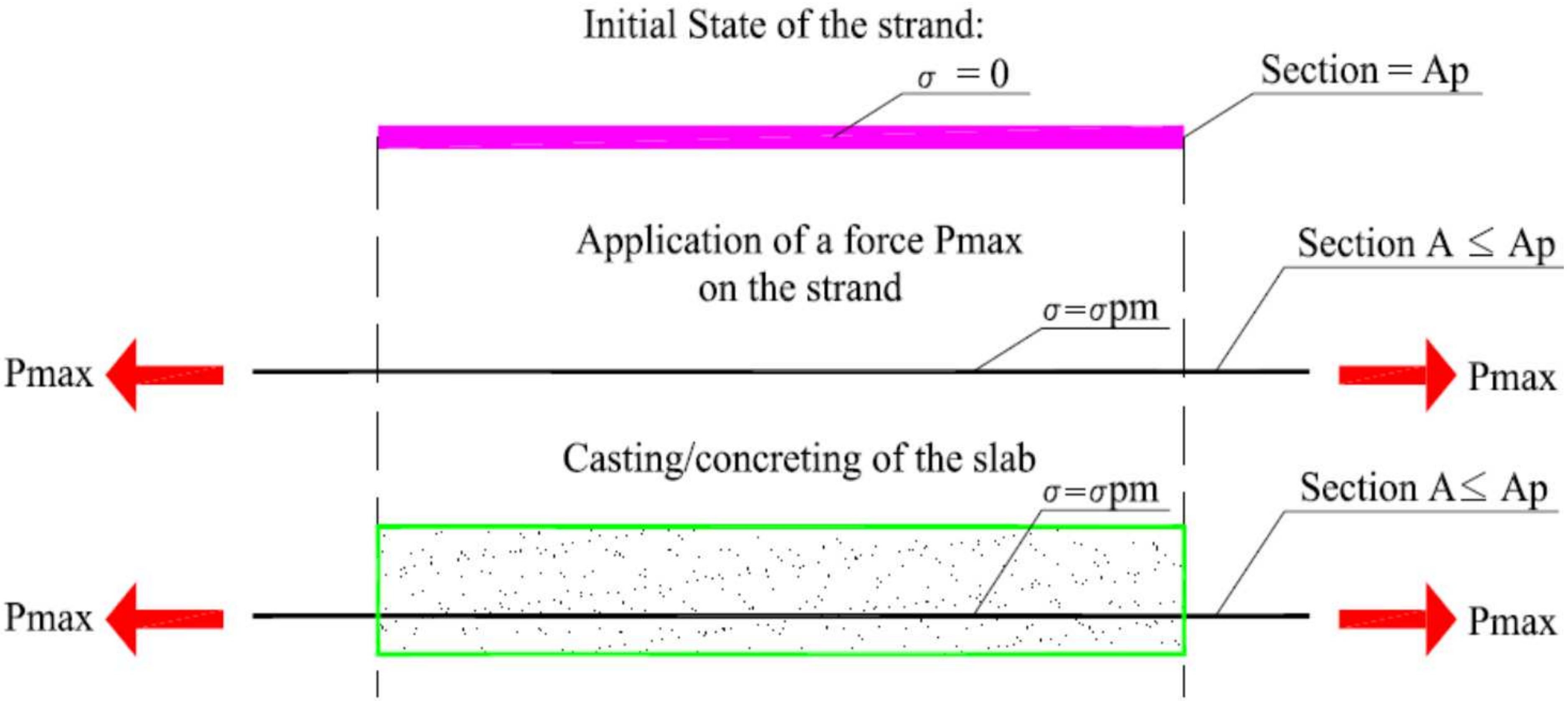
Where d_g is the maximum size of aggregate

Summary of the structural tendon position



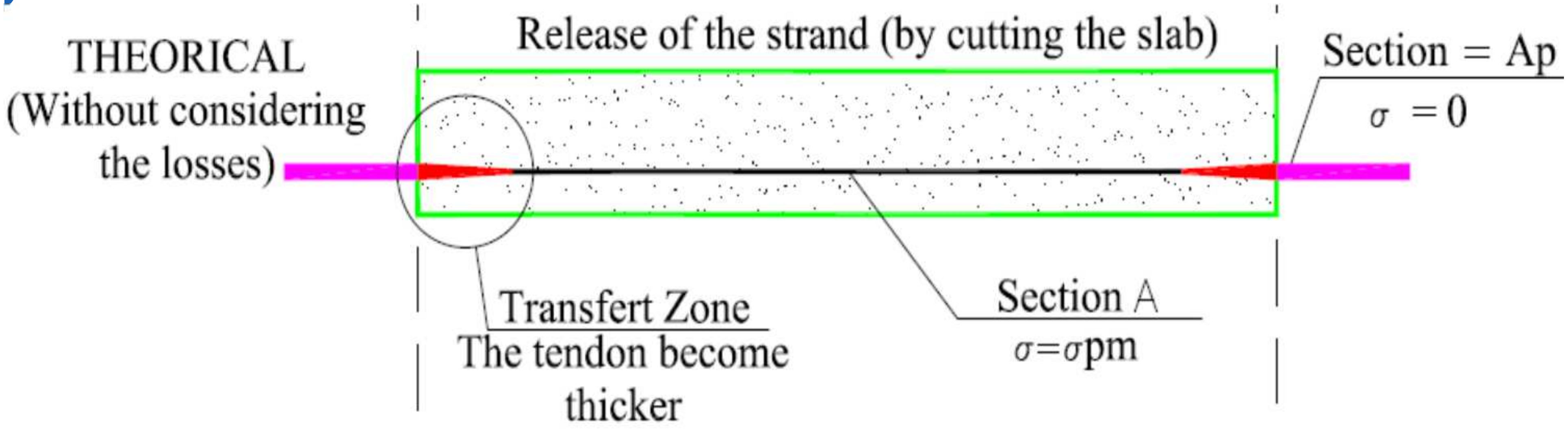
General on transfer of prestressing

- The strands (or wires) are strained to a force P_{max} prior to casting. They undergo an elongation and their diameter decreases A<Ap;

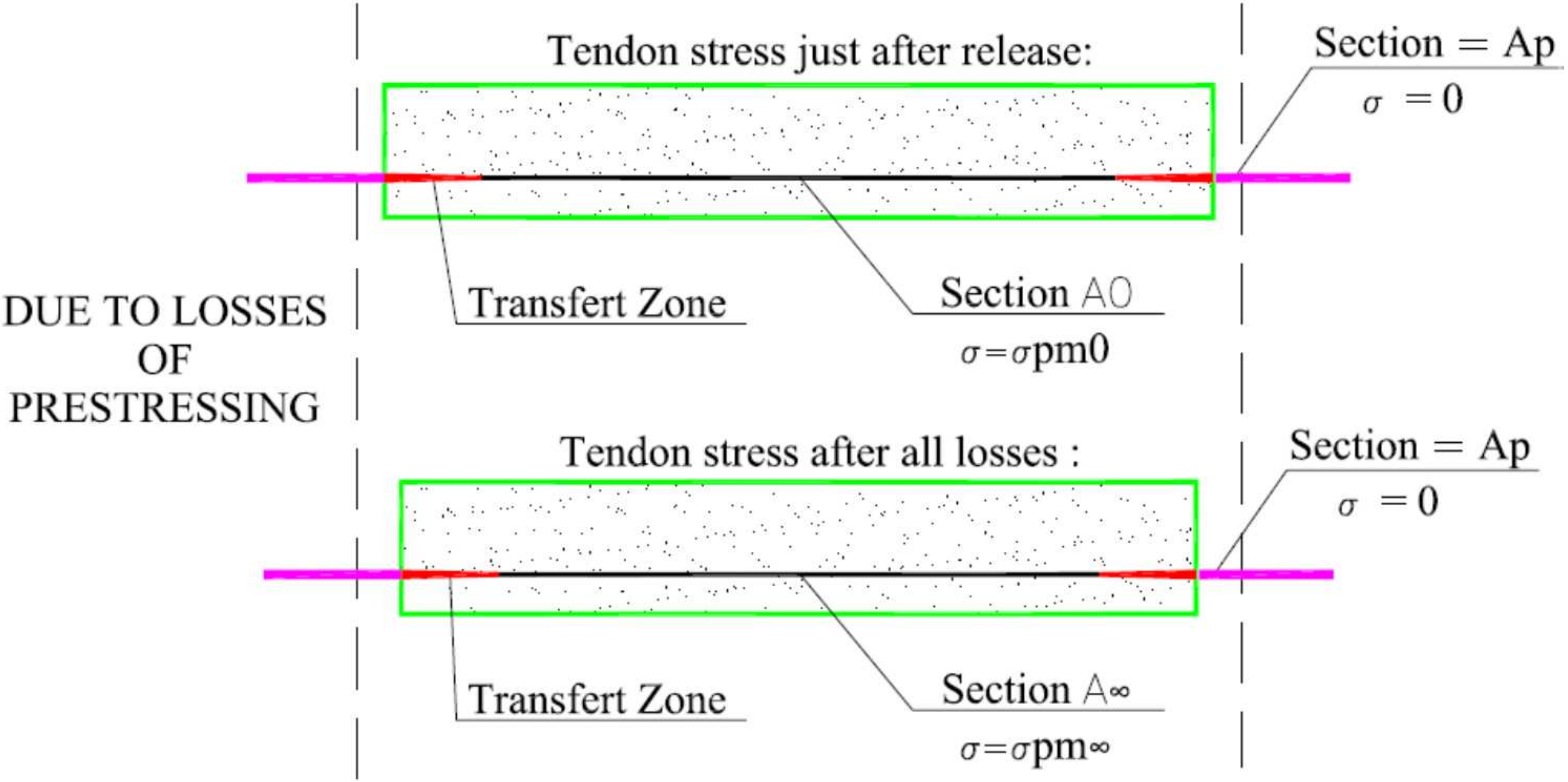


General on transfer of prestressing

- When released after the concrete is sufficiently hardened, the strands exercise the force P_{max} on the slab through the steel-concrete bond



General on transfer of prestressing



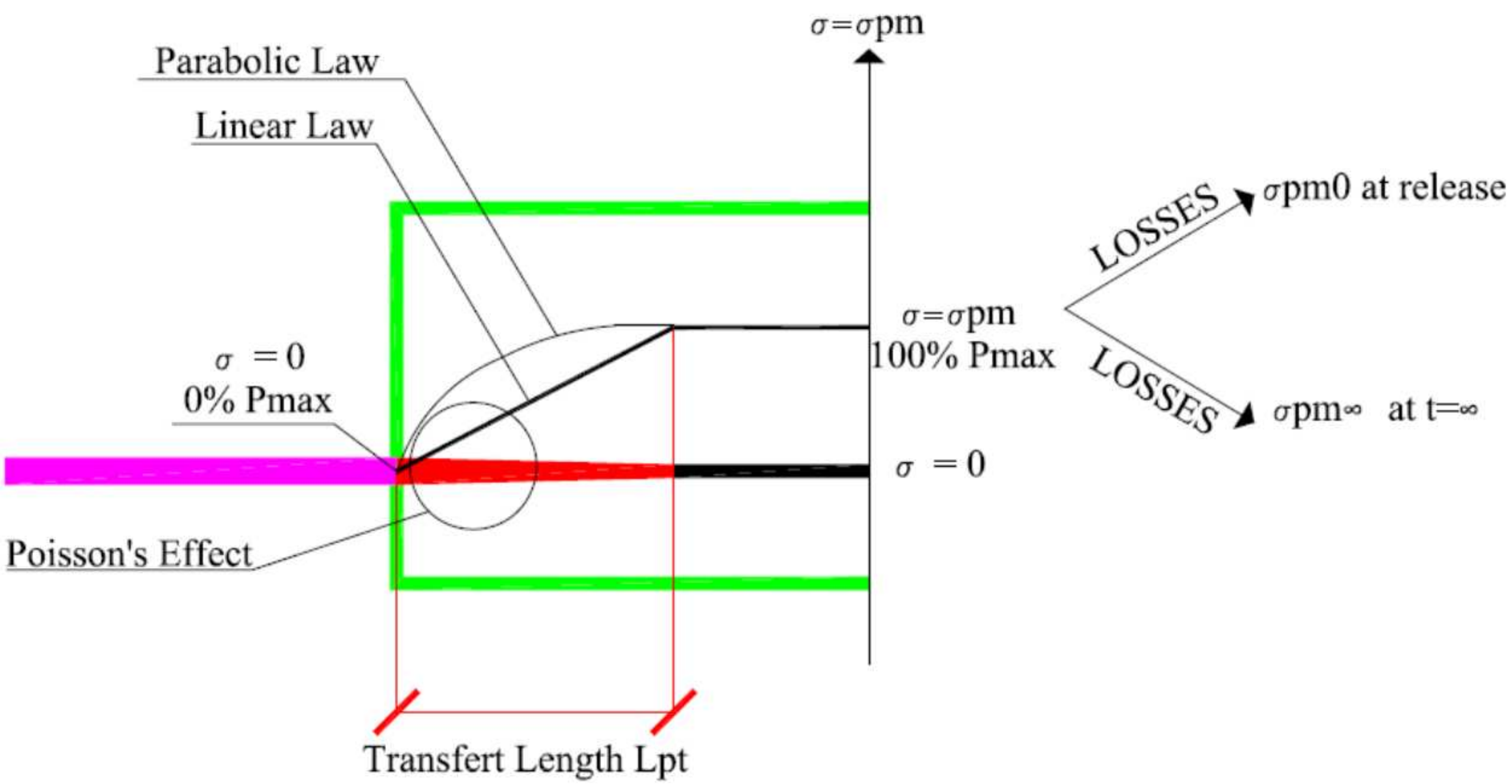
General on transfer of prestressing

- The difference $P_{max} - P_{mo} = \Delta P_i$ (immediate losses due to elastic deformation of concrete, relaxation of the strand...)

- Indeed, after sawing the slab, the tendon try to return to its initial state (section Ap with $\sigma = 0$). But the concrete-steel bond is opposed to this shortening. Friction (by Poisson's effect) and chemical bond is opposed to the slippage of the cable from the edge of the slab to a length called lpt (transfer length)

General on transfer of prestressing

- In this transmission zone, prestressing develops from zero to 100% following a parabolic law which for conveniency's and safety's sake can be assimilated to a linear growth having a length lpt



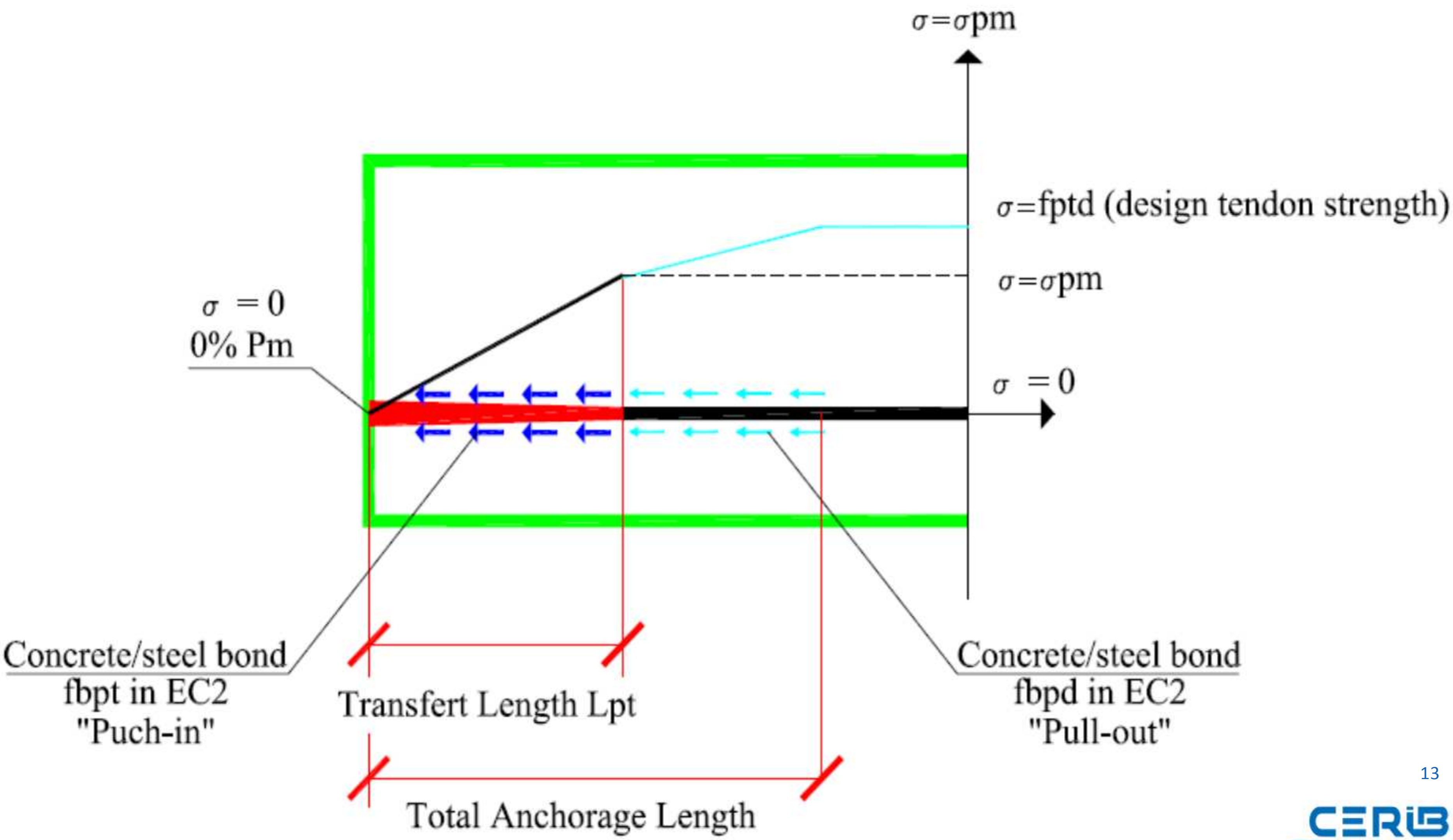
General on transfer of prestressing

- The reduction of stress in the steel due to the relaxation under tension and due to creep and shrinkage of the concrete under permanent loads leads to a final stress in the tendon $\sigma_{pm\infty}$:

$$P_{m\infty} - P_{mo} = \Delta P_{\infty}$$

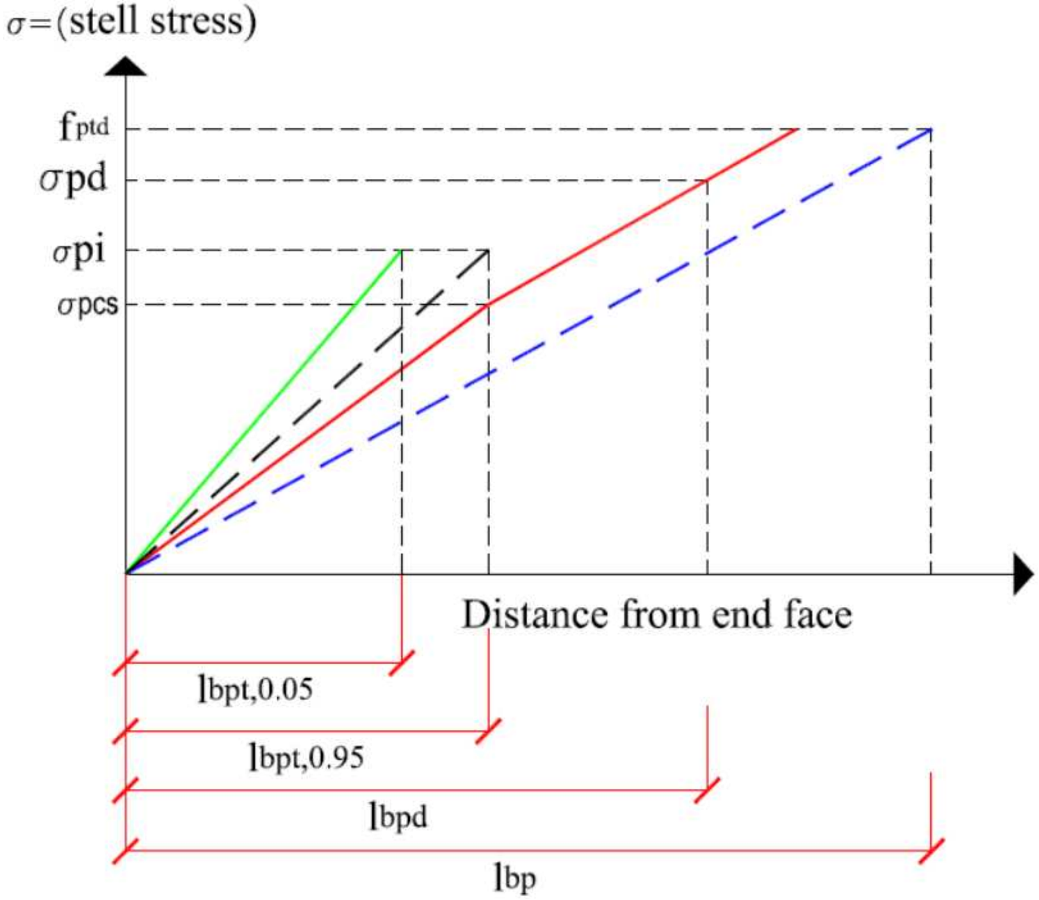
- 2 different bond situations should be considered due to the transverse deformation of the tendon:
  - ➢ A push-in along lpt where the tendon become thicker at release
  - ➢ A pull-out which refers to the anchorage when the steel stress is increased due to loading

General on transfer of prestressing

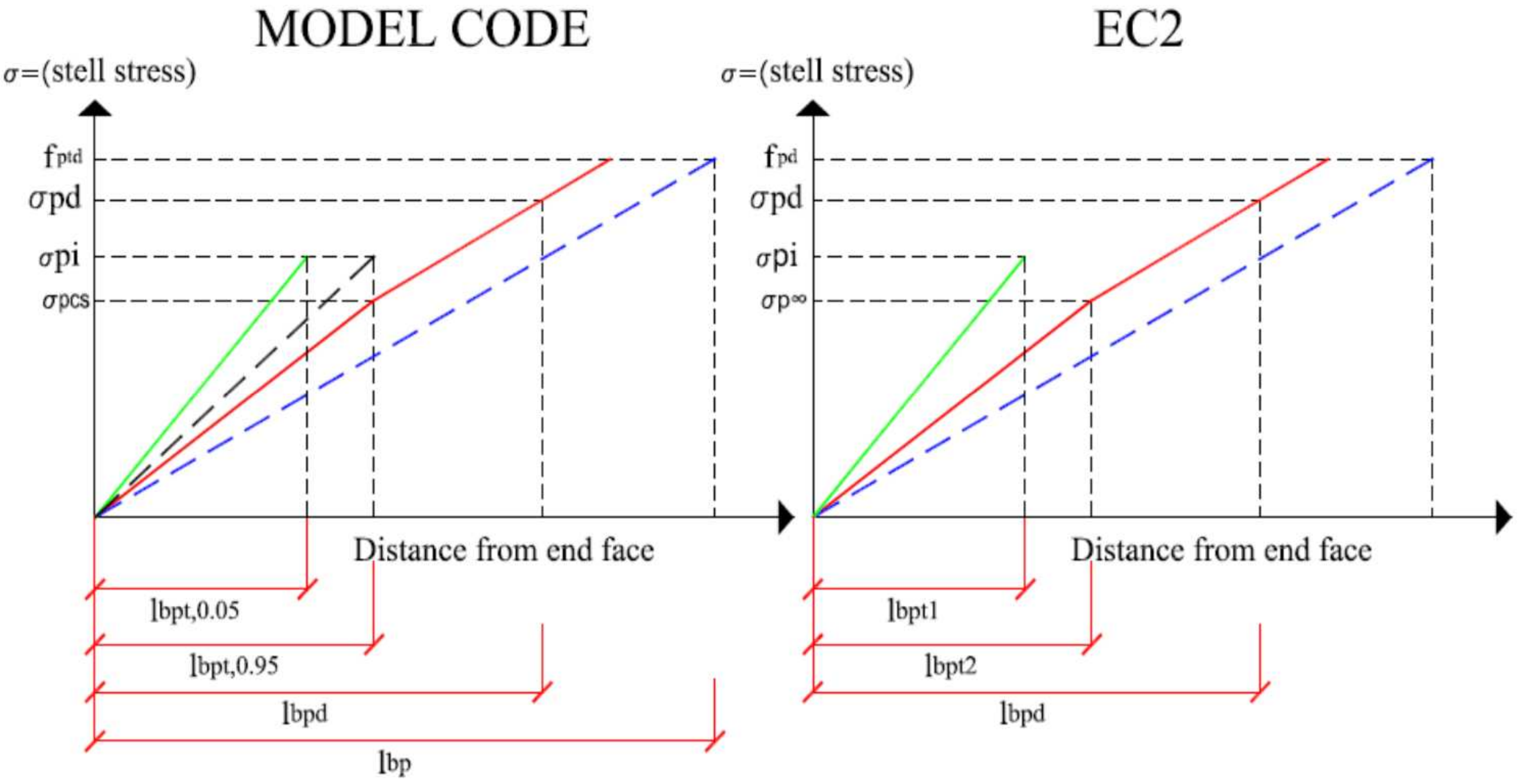


Transfer of prestressing in Model Code

- This results in a bilinear diagram for the embedment length that is required to develop the design steel stress f_{ptd} (same as EC2) :



Comparison Model Code – EC2



Design bond strength

- Whereas EC2 determines directly the transmission length, MC 2010 starts with a basic anchorage length

- The design value of the bond strength for prestressing tendon is:

$$f_{bpd}=\eta_{p1}\eta_{p2}\, f_{ctd}$$

Where :

- $f_{ctd} = f_{ctk}(t)/\gamma_c$ is the lower design concrete tensile stenght; for the transmission length at the time of release, for the anchorage length at 28 days

Design bond strength

- η_{p1} takes into account the type of prestressing tendon:
  - ☐ η_{p1} = 1.4 for indented and crimped wires
  - ☐ η_{p1} = 1.2 for 7-wire strands

- η_{p2} takes into account the position of the tendon:
  - ☐ η_{p2} = 1.0 for all tendons with an inclination of 45-90° with respect to the horizontal during concreting
  - ☐ η_{p2} = 1.0 for all horizontal tendons which are up to 25 cm from the bottom or at least 30 cm below the top of the concrete section during concreting
  - ☐ η_{p2} = 0.7 for all other cases

Basic anchorage length

- The basic anchorage length defines the length required to develop the full strength in an UNTENSIONED tendon:

$$l_{bp} = \frac{A_{sp}}{\varnothing \pi} \frac{f_{ptd}}{f_{bpd}}$$

Where:

- $f_{ptd} = f_{ptk}/\gamma_s$ is the steel design tendon strength
- A_{sp} = area of the cross section of the tendon
- Ø is the nominal diameter of the tendon
- $\frac{A_{sp}}{\varnothing \pi} = \frac{\varnothing}{4}$ for circular cross section (=0.25Ø) and $\frac{7\varnothing}{36}$ for 7-wire strands (≈0.19Ø)

Transmission length

- The transmission length of a pretensioned tendon is:

$$l_{bpt} = \alpha_{p1}\alpha_{p2}\alpha_{p3}l_{bp}\frac{\sigma_{pi}}{f_{ptd}}$$

Where:

- ➢ σ_{pi} is the steel stress just **after release**
- ➢ α_{p1} considers the type of release:
  - ❑ α_{p1} = 1 for gradual release
  - ❑ α_{p1}= 1.25 for sudden release

Transmission length

- α_{p2} considers the action effect to be verified
  - ☐ α_{p2} = 1 for calculation of anchorage length when moment and shear capacity is considered (and for $l_{bpt0.95}$)
  - ☐ α_{p2} = 0.5 for verification of transverse stress in anchorage zone (and for $l_{bpt0.05}$)

- α_{p3} considers the influence of bond situation
  - ☐ α_{p3} = 0.5 for strands
  - ☐ α_{p3} = 0.7 for indented or crimped wires

Design anchorage length

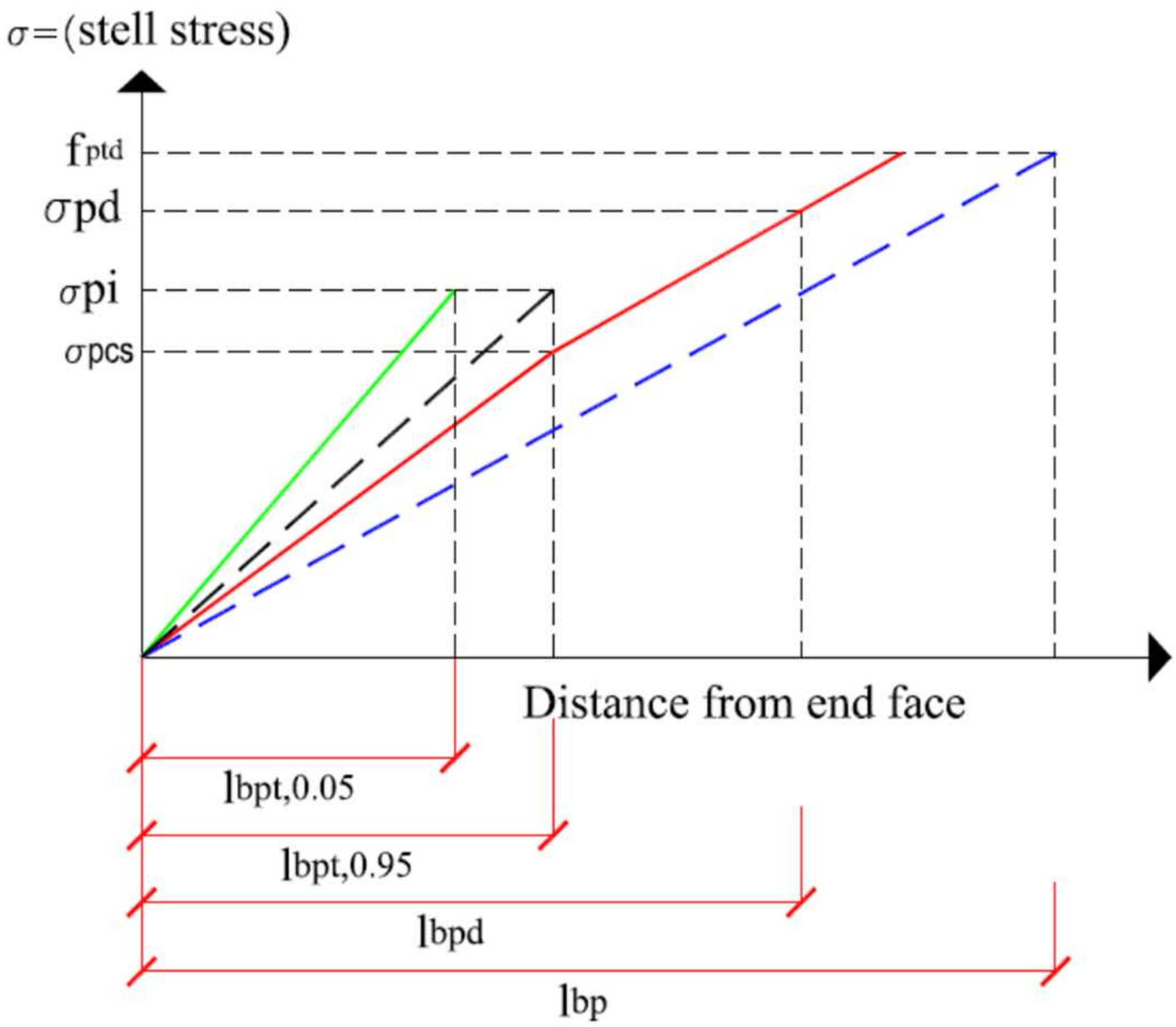
- The design anchorage length of a pretensioned tendon is:

$$l_{bpd} = l_{bpt} + l_{bp} \frac{\sigma_{pd} - \sigma_{pcs}}{f_{ptd}}$$

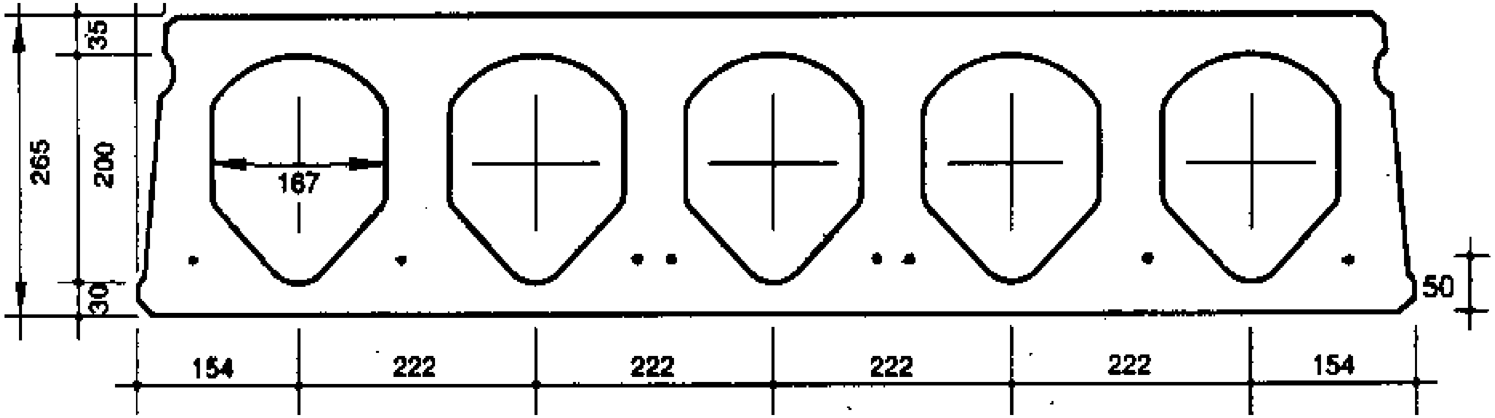
Where:

- σ_{pd} is the tendon stress under design load ($\sigma_{pd} \leq f_{ptd}$)
- σ_{pcs} is the tendon stress due to prestress after all losses

Design anchorage length



Example – Data



- Slab type: HC 265
- Concrete strength at transfer of prestress: f_{ck} = 35 MPa; $f_{ctk0,05}$ = 2.25 MPa
- Concrete strength in service: f_{ck} = 50 MPa; $f_{ctk0,05}$ = 2.85 MPa
- Partial security factor: γ_c = 1,35 (Annex A EC2)

Example – Data

- Prestressing:

➢ 8 ø ⅜’ strands (Ø= 9,3 mm)

➢ Steel characteristic ultimate stress:
$f_{pk,EC2}$ = 1860 Mpa (= $f_{ptk,MC}$)

➢ Steel design ultimate stress:
$\sigma_{pd,EC2} = f_{pk} / \gamma_s$ = 1860/1,15 = 1617 Mpa (= $f_{ptd,MC}$)

➢ Steel stress at transfer: $\sigma_{pm0,EC2}$ = 1080 Mpa ($\sigma_{pi,MC}$)

➢ Steel stress in service: $\sigma_{pm\infty,EC2}$ = 872 MPa ($\sigma_{pcs,MC}$)

Example according to EC2

- Transfer length of prestress:

  - $f_{ctd} = \alpha_{ct} \cdot f_{ctk} / \gamma_c = 1.0 \text{ x } 2.25 / 1.35 = 1.67$ Mpa
  - $f_{bpt} = \eta_{p1}\, \eta_1\, f_{ctd} = 3.2 \text{ x } 0.7 \text{ x } 1.67 = 3.73$ Mpa
  - $l_{pt} = \alpha_1\, \alpha_2\, \phi\, \sigma_{pm0} / f_{bpt} = 1.0 \text{ x } 0.19 \text{ x } 9.3 \text{ x } 1080 / 3.73 =$ 512 mm

$$\mathbf{l_{pt1} = 0.8\, l_{pt} = 409\ mm}$$

$$\mathbf{l_{pt2} = 1.2\, l_{pt} = 614\ mm}$$

Example according to EC2

- Anchorage length:

➢ $f_{ctd} = f_{ctk} / \gamma_c = 2.85 / 1.35 = 2.11$ Mpa

➢ $f_{bpd} = \eta_{p2}\, \eta_1\, f_{ctd} = 1.2 \times 0.7 \times 2.11 = 1.77$ Mpa

➢ $l_{bpd} = l_{pt2} + \alpha_2\, \phi\, (\sigma_{pd} - \sigma_{pm\,\infty}) / f_{bpd} = 613 + 0.19 \times 9.3\,(1617 - 872) / 1.77 = 1356$ mm

l_{bpd}= 1356 mm

Example according to MC

- Basic anchorage length at release:
  - $f_{bpd} = \eta_{p1}\ \eta_{p2}\ f_{ctd}$ = 1.2 x 0.7 x 2.25/1.35 = 1.4 Mpa
  - $l_{bp} = \frac{A_{sp}}{\emptyset\pi}\frac{f_{ptd}}{f_{bpd}} = 0.19\ \emptyset\ \frac{f_{ptd}}{f_{bpd}}$ = 0.19 x 9.3 x 1617/1.4 = 2040 mm

- Transmission length:
  - $l_{bpt0,05} = l_{bp}\ \alpha_{p1}\alpha_{p2}\alpha_{p3}\frac{\sigma_{pi}}{f_{ptd}}$ = 2040 x 1 x **0.5** x 0.5 x 1080/1617 = 340 mm
  - $l_{bpt0,95} = l_{bp}\ \alpha_{p1}\alpha_{p2}\alpha_{p3}\frac{\sigma_{pi}}{f_{ptd}}$ = 2040 x 1 x **1** x 0.5 x 1080/1617 = 681 mm

Example according to MC

- Design anchorage length in service :

➢ $f_{bpd} = \eta_{p1}\ \eta_{p2}\ f_{ctd}$ = 1.2 x 0.7 x 2. 85/1.35 = 1.77 Mpa

➢ $l_{bp} = \frac{A_{sp}}{\emptyset\pi}\frac{f_{ptd}}{f_{bpd}}$ = 0.19 $\emptyset\ \frac{f_{ptd}}{f_{bpd}}$ = 0.19 x 9.3 x 1617/1.77 = 1611mm

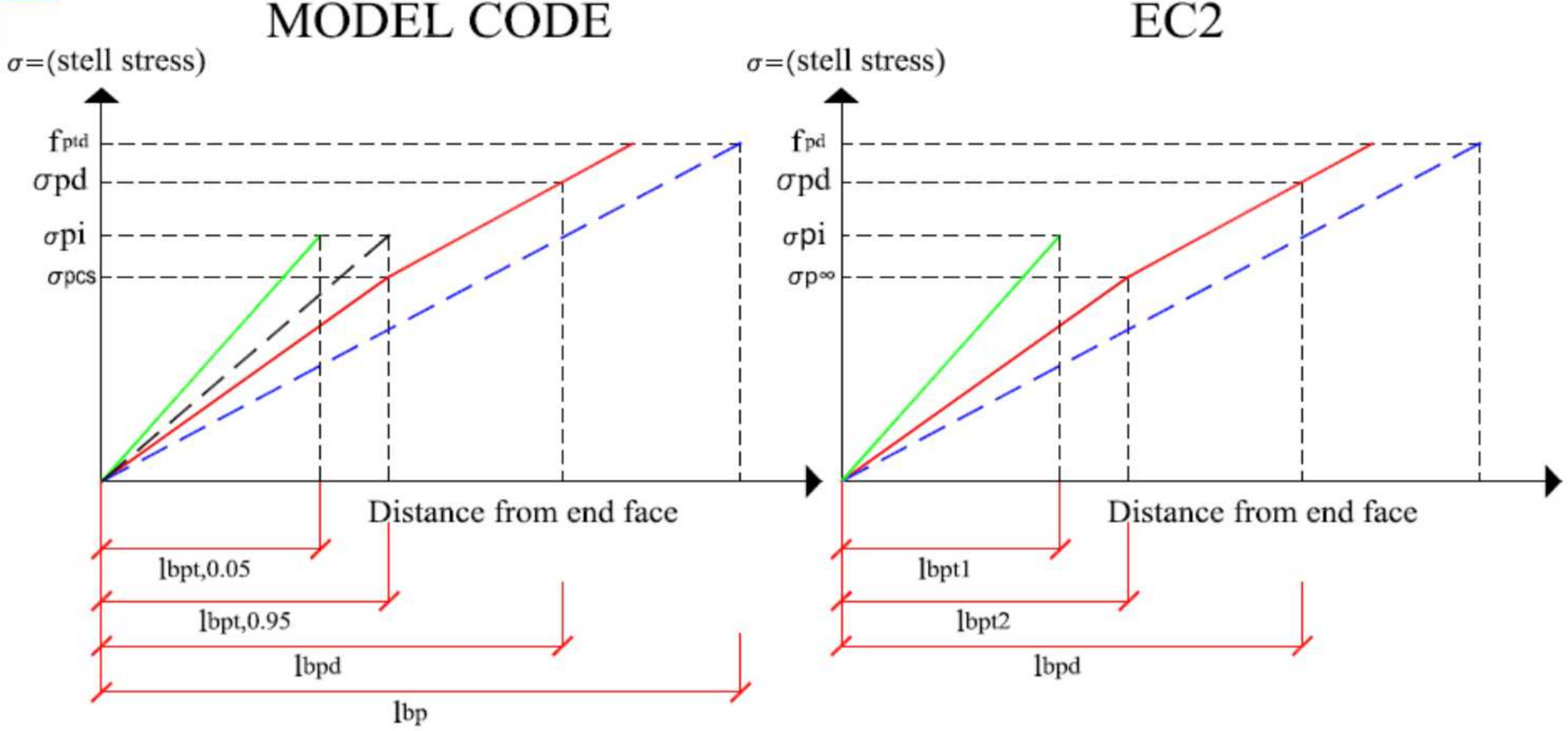
➢ $l_{bpd} = \ l_{bpt0,95} + l_{bp}\ \frac{\sigma_{pd}-\sigma_{pcs}}{f_{ptd}}$ = 681 + 1611 x (1617 – 872)/1617

= 1423 mm

Example comparison EC2 – MC

Model Code
$l_{pt0,05}$ = 340 mm
$l_{pt0,95}$ = 681 mm
l_{bpd} = 1422 mm

EC2
l_{pt1} = 409 mm
l_{pt2} = 614 mm
l_{bpd} = 1356 mm

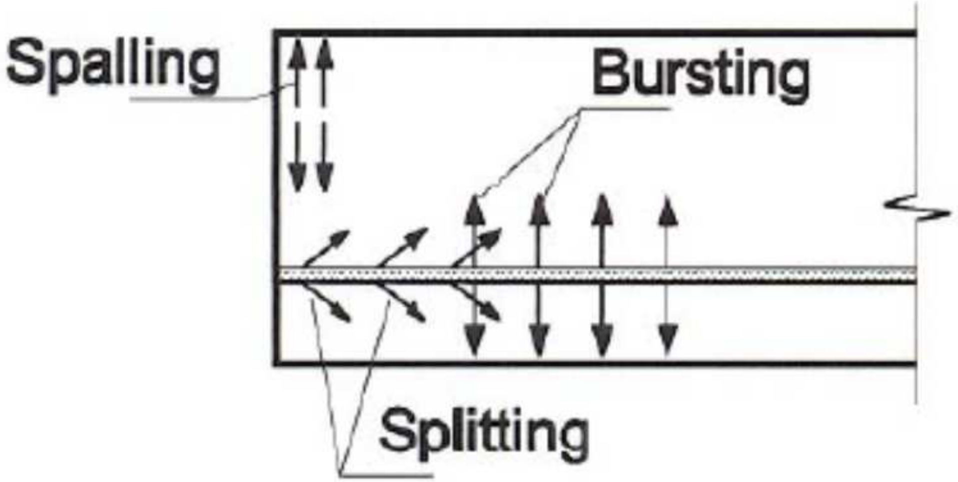


Stresses in the transmission zone

- If the slab section is without bending cracks along l_{bpd}, no anchorage check is necessary

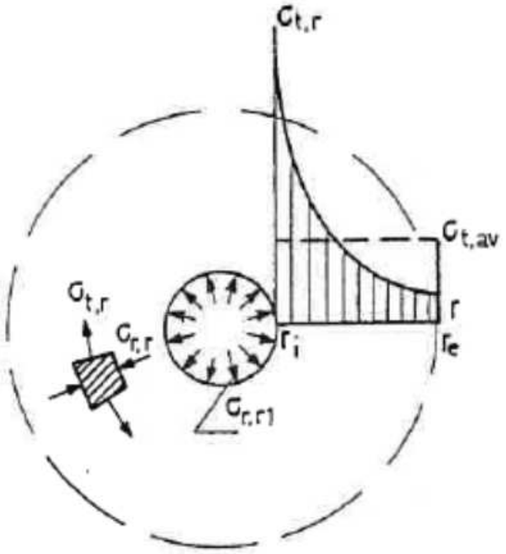
- In the transmission zone ($x<l_{pt}$), 3 types of tensiles stresses should be distinguished:

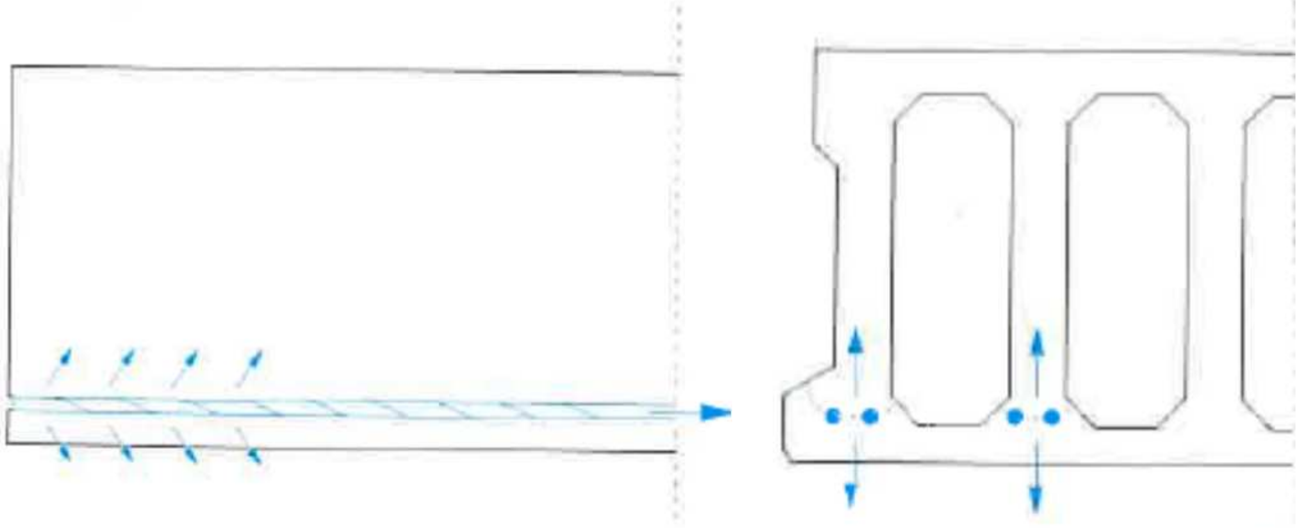
➢ Splitting
➢ Spalling
➢ Bursting



Splitting

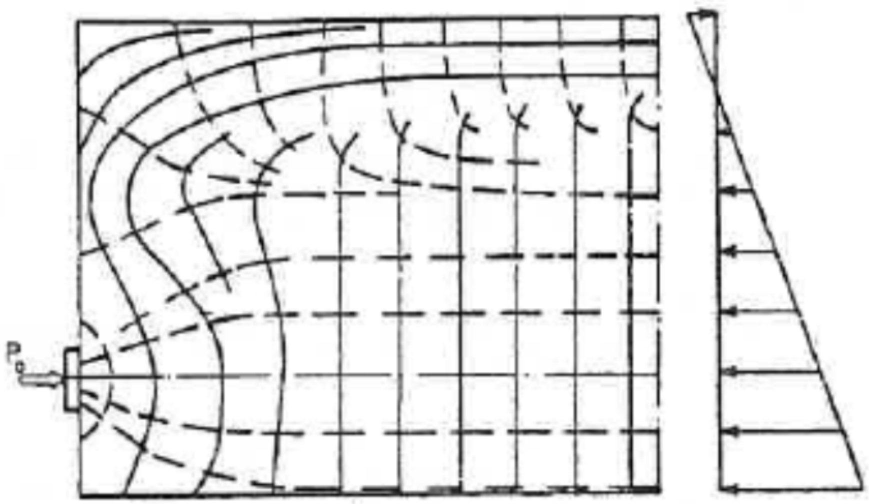
- The transfer of forces between the tendon and the concrete involves stresses parallel to the axis of the tendon (bond) but also perpendicular. Theses compressive stresses are radial and generate circumferential tensil stresses (like a barrel):





Bursting

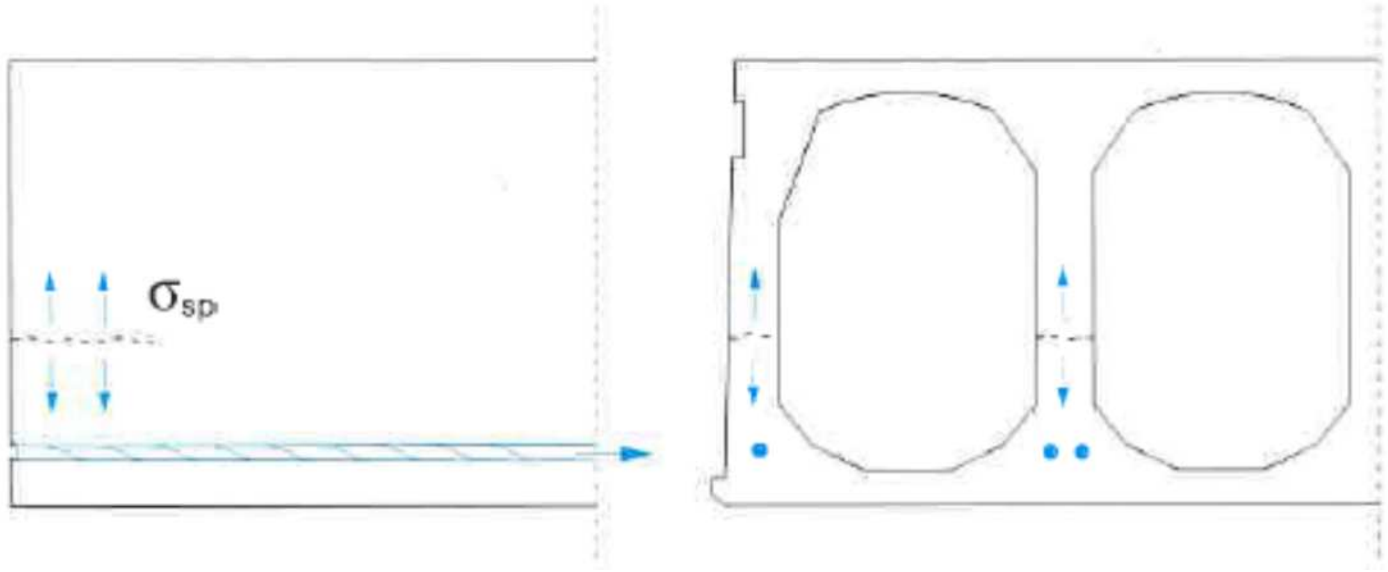
- The application of an external point load at the end of the slab leads to these principal stress trajectories:



- The phenomenon is identical in the case of prestressing with the difference that the load is applied gradually on l_{pt}

Spalling

- These stresses are also caused by the development of prestressing in the concrete of the slab end where only the lower part begins to be prestressed:



- These vertical tensile force lead to horizontal cracks which are commonly known as « crocodile mouths »

Checking in the transmission zone

- Splitting and bursting are avoided by maintaining the distance between strands and cover requirements indicated at the beginning (c_{min} and i_h/i_v)

- For spalling, EN1168 gives the criterion to be respected $\sigma_{sp} \leq f_{ct}$ and the equation for the calculation of the spalling stress σ_{sp} :

$$\sigma_{sp} = \frac{P_o}{b_w e_o} \times \frac{15\,\alpha_e^{2,3} + 0{,}07}{1 + \left(\frac{\ell_{pt1}}{e_o}\right)^{1,5} \left(1{,}3\,\alpha_e + 0{,}1\right)}$$

$$\text{with } \sigma_{sp} = \frac{P_o}{b_w e_o} \times \frac{15\,\alpha_e^{2,3} + 0,07}{1 + \left(\frac{\ell_{pt1}}{e_o}\right)^{1,5} \left(1,3\,\alpha_e + 0,1\right)}$$

$$\text{and} \qquad \alpha_e = \frac{(e_o - k)}{h} \geq 0$$

f_{ct}	is the value of the tensile strength of the concrete deduced at the time that the prestress is released on the basis of tests;
P_o	is the initial prestressing force just after release in the considered web or the total prestressing force of the slab in case of solid slabs;
b_w	is the thickness of the individual web or the total width b of the slab in case of a solid slab;&
e_o	is the eccentricity of the prestressing steel;
l_{pt1}	is the lower design value of the transmission length;
k	is the core radius taken equal to the ratio of the section modulus of the bottom fibre and the net area of the cross section (W_b/A_c);

Slippage of strands into slab end

- The slippage is directly related to the anchorage of tendons
- As prestress transfert is of mayor importance for structural behavior of HC slab, slippage should be measure
- But this slippage must remain within acceptable limits
- The theorical slippage Δl_o can be calculated according to EN13369:

$$\Delta l_0 = 0.4 l_{bpt0.95} \frac{\sigma_{pi}}{E_p}$$

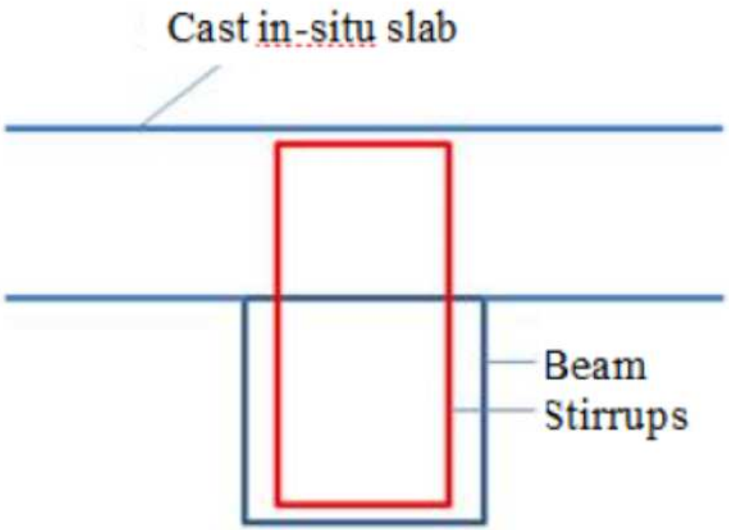
- The maximum allowable slippage of a single strand shall not exceed 1.3 Δl_o (and mean value of all strands $\leq \Delta l_o$)

Slippage of strands into slab end

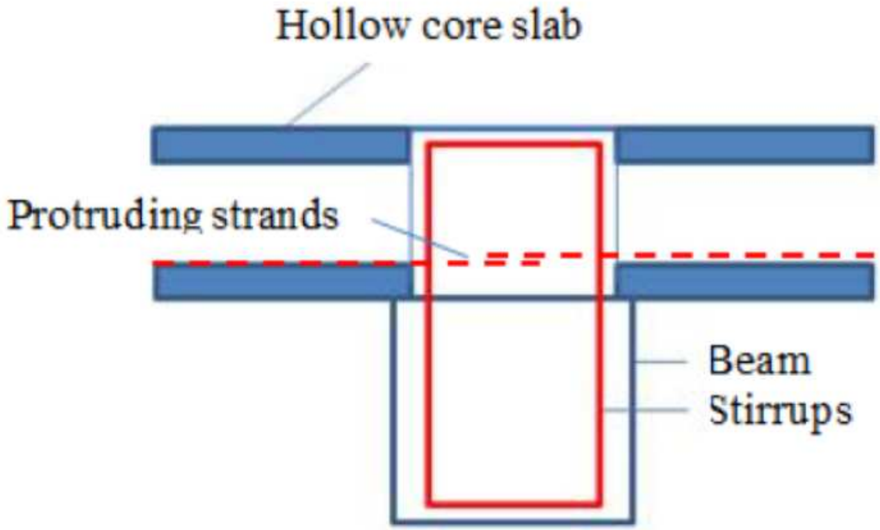
Δl_o higher than permissible

Protruding strands

In the 1970's, France has developed HC slab with protruding strands to avoid to repositioning of projecting stirrups in cast in-situ or to enable the continuity of vertical wall reinforcement:



Solution a1: cast in-situ slabs



Solution a2: hollow core slabs

Protruding strands

The length of the HC units is realised during manufacture, by manual or semi-automatic removal of a strip of fresh concrete with a width of 2 times the required tendon's protruding lenght :

Protruding strands

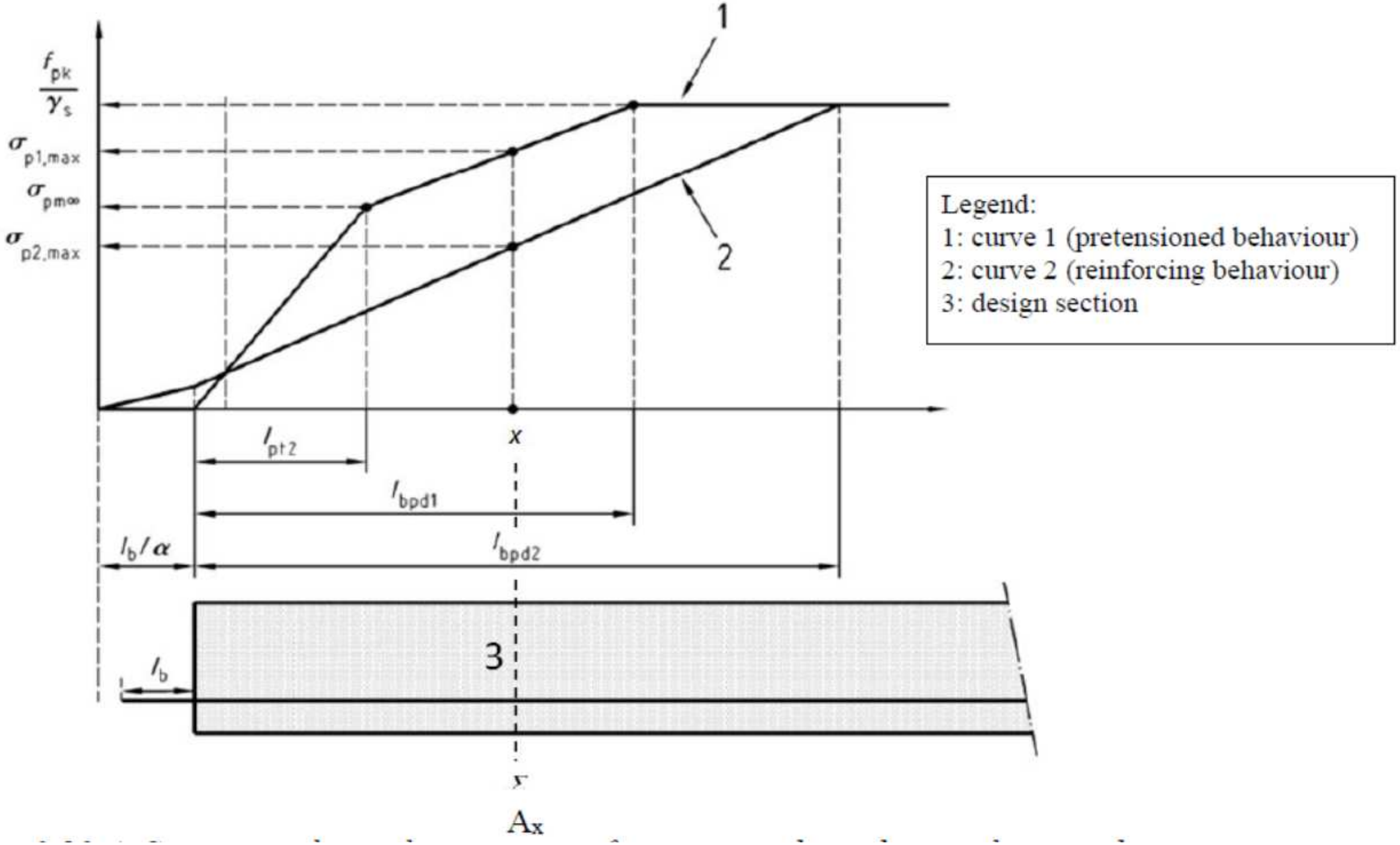
- The transmission zone ($x<l_{pt}$) is unchanged from the end of the slab between a traditional system and a system with protruding strands ;

- The design anchorage length l_{bpd} is unchanged if the section is uncracked ;

- On the other hand, the protruding strands give the slab a longer basic anchorage length (since it is measured from the end of protruding strand) useful when the slab is cracked along l_{pt} or l_{bpd}

Protruding strands

Stresses in the anchorage zone of slabs with protruding strands (according NF DTU 23.2):



Legend:
1: curve 1 (pretensioned behaviour)
2: curve 2 (reinforcing behaviour)
3: design section