EPFL

# Steel-concrete composite beams - Part C -

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CIVIL526 – Steel Structures

# Content

- Connection
- Longitudinal shear
- Partial connection
- Appendices

References : TGC 10 § 5.8.6 and TGC 11 § 10.5.5

# Types of connection

- Two types of connection:

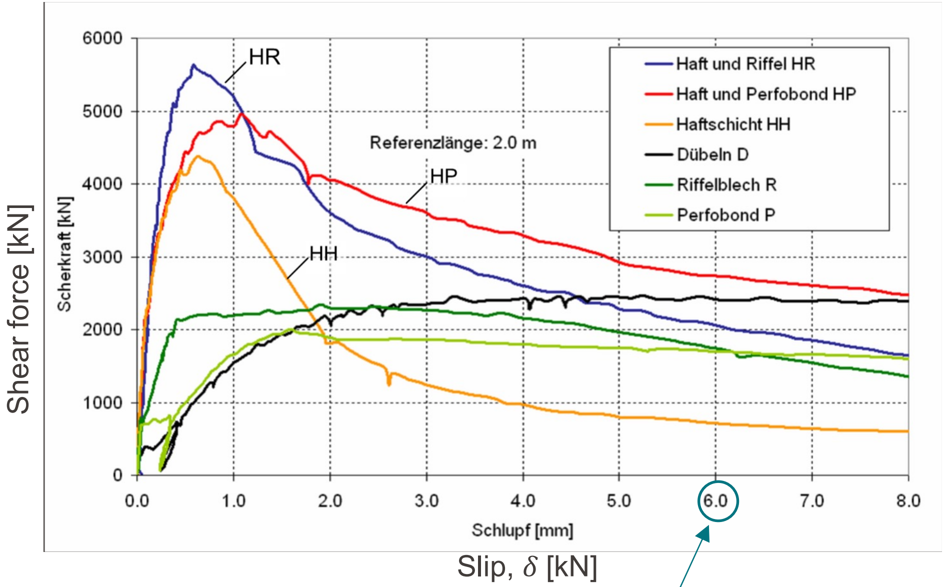
total or partial

| The ultimate strength of the composite beam is not limited by the strength of the connection. | The ultimate strength of the composite beam is limited by the strength of the connection. |
| --- | --- |
| • mandatory for bridges<br>• often used in buildings | • only in buildings<br>• only if the strength of the beam section is determined by a plastic calculation<br>• the connector must be flexible |

# Connection : design steps

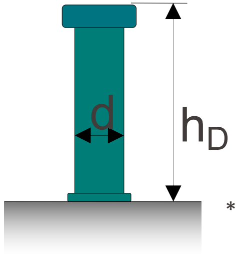
1. Calculate the horizontal shear force acting on the steel-concrete interface to be absorbed by the connectors
2. Compute the shear resistance of a connector
3. Determine the number of connectors required by elastic or plastic calculation, depending on the analysis adopted for the strength of the composite (mixed) section
4. Place the connectors on the surface of the steel beam flange, respecting certain geometric criteria

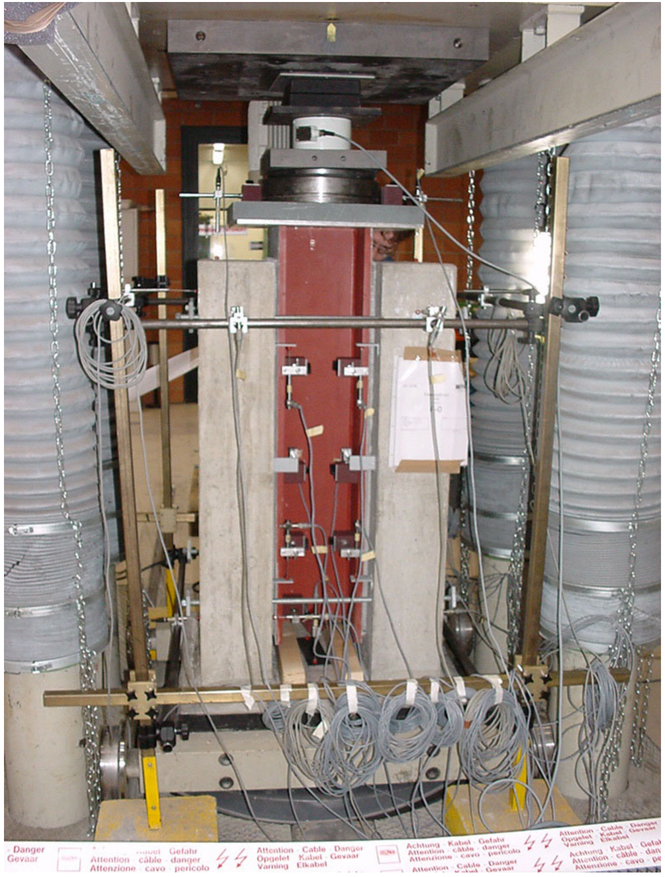
# Connection resistance, push-out tests




Limit for flexible connectors*

$\leftrightarrow$ goujons: $h_d \geq 4d$

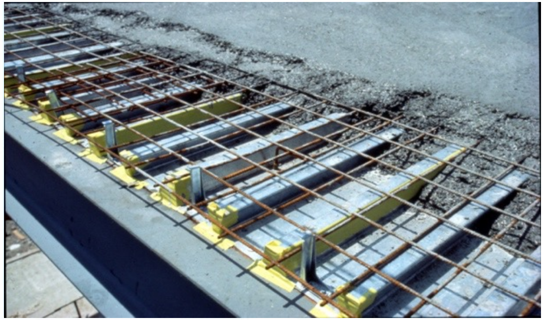


* For connectors other than studs, check their deformability $\delta_{uk} \geq 6$ mm by calculation or tests in accordance with EN 1994-1-1.

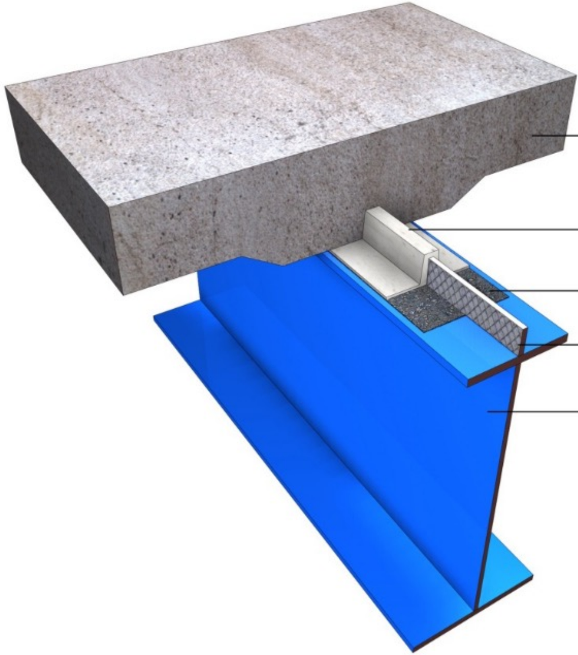
# Recall: Types of connectors

Headed studs



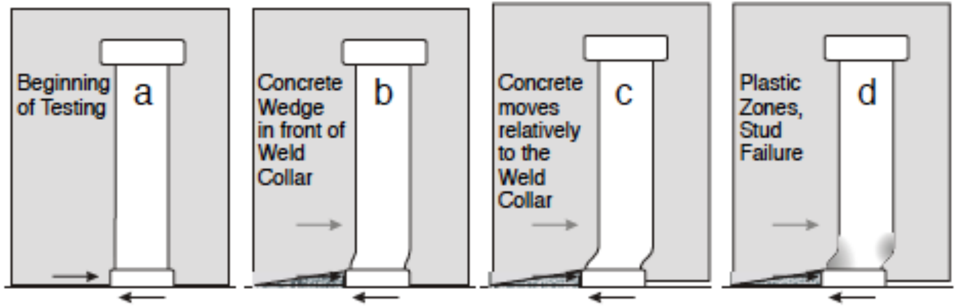
Hilti studs

Perfobond connectors



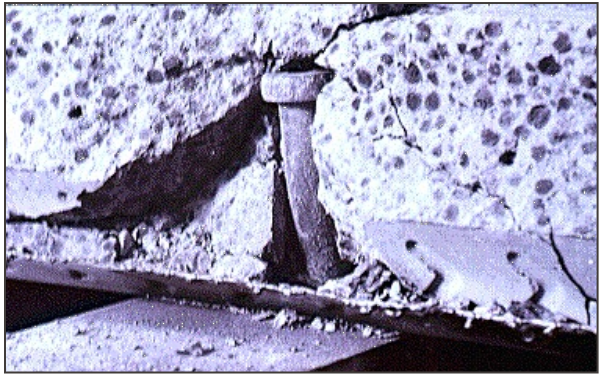
# Headed stud connection, breaking modes






By shear plastification of the stud shank

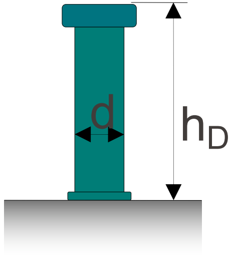
No plastification in the welding if proper execution & control !



Crushing of concrete (caused by bending of the stud)

# Stud connection resistance, calculation






- Characteristic resistance :

$$P_{Rk} = \min(P_{Rk}^1; P_{Rk}^2)$$

$$P_{Rk}^1 = \frac{0.8 f_{uD} \pi d^2}{4} \quad et \; P_{Rk}^2 = 0.29 d^2 \sqrt{f_{ck} E_{cm}}$$

Failure by shearing of the base ($16 \le d \le 25$ mm)

Failure due to crushing of the concrete at the base ($20 \le f_{ck} \le 50$ N/mm$^2$)

- Ultimate design strength : Plastic/elastic calculation

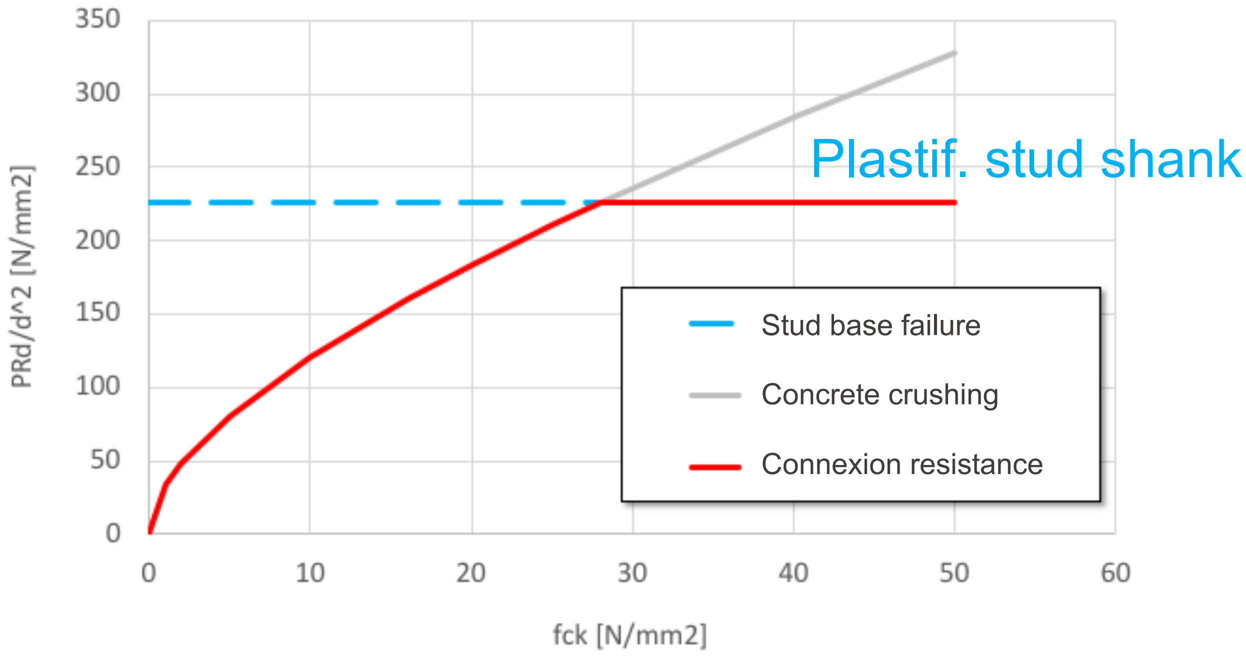
Calcul plastique $P_{pl,Rd} = \frac{P_{Rk}}{\gamma_V}$ avec $\gamma_V = 1.25$

Calcul élastique $P_{el,Rd} = 0.75 \frac{P_{Rk}}{\gamma_V}$

SIA 264 §6.1.2.1

# Stud connection resistance, calculation





# Stud strength, calculation values

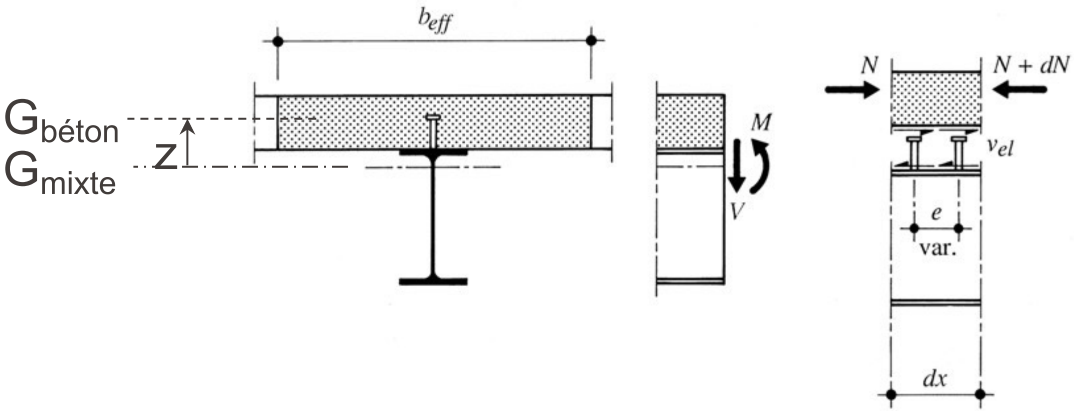


| Diamètre du goujon, d | Calcul plastique | | | Calcul élastique | | | |
|---|---|---|---|---|---|---|---|
| | Béton C 20/25 | Béton C 25/30 | Béton C 30/37 | Béton C 16/20 | Béton C 20/25 | Béton C 25/30 | Béton C 30/37 |
| 13 mm | 31 kN | 35 kN | 38 kN | 20 kN | 23 kN | 27 kN | 29 kN |
| Building -> 16 mm | 47 kN | 54 kN | 58 kN | 30 kN | 35 kN | 40 kN | 43 kN |
| 19 mm | 66 kN | 76 kN | 82 kN | 43 kN | 49 kN | 57 kN | 61 kN |
| Bridge -> 22 mm | 88 kN | 101 kN | 109 kN | 58 kN | 66 kN | 76 kN | 82 kN |

$(f_{u,D} = 450\ \text{N/mm}^2)$.

# Elastic calculation of the connection

- In each cross-section with abscissa x :




TGC 10 fig. 5.43

Variation in N along the length dx, i.e. the « slip » or « shearing force » at the interface :

$$v_{el,Ed}(x) = \frac{S_{béton}}{n_{el} I_{mixte}} V_{Ed}(x) \qquad v_{el,Ed}(x) = \sum \frac{S_{c,i}}{n_{el,i} I_{b,i}} V_{Ed,i}(x)$$

$v_{Ed,i}(x)$ from actions on composite section ! (after the connection has been made)

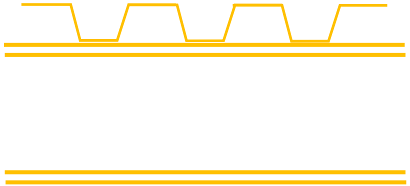
# Elastic calculation of the connection

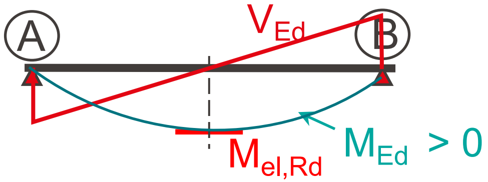
- Determining the number of connectors (e.g. nb/m) : $N_{connect} = \frac{E_d}{R_d} = \frac{v_{el,Ed}(x)dx}{P_{el,Rd}}$

Connector resistance

- The number of connectors results in a longitudinal spacing between the transverse rows
- The number varies along the beam (with the shear force) so does the nb/m, or the longitudinal spacing between connectors, $e_1$
- Number of connectors per row: $n_{connect} = \frac{v_{el,Ed}(x)}{P_{el,Rd}} e_1$

→ Typically: $150 < e_1 < 400$mm





# Example of connectors distribution

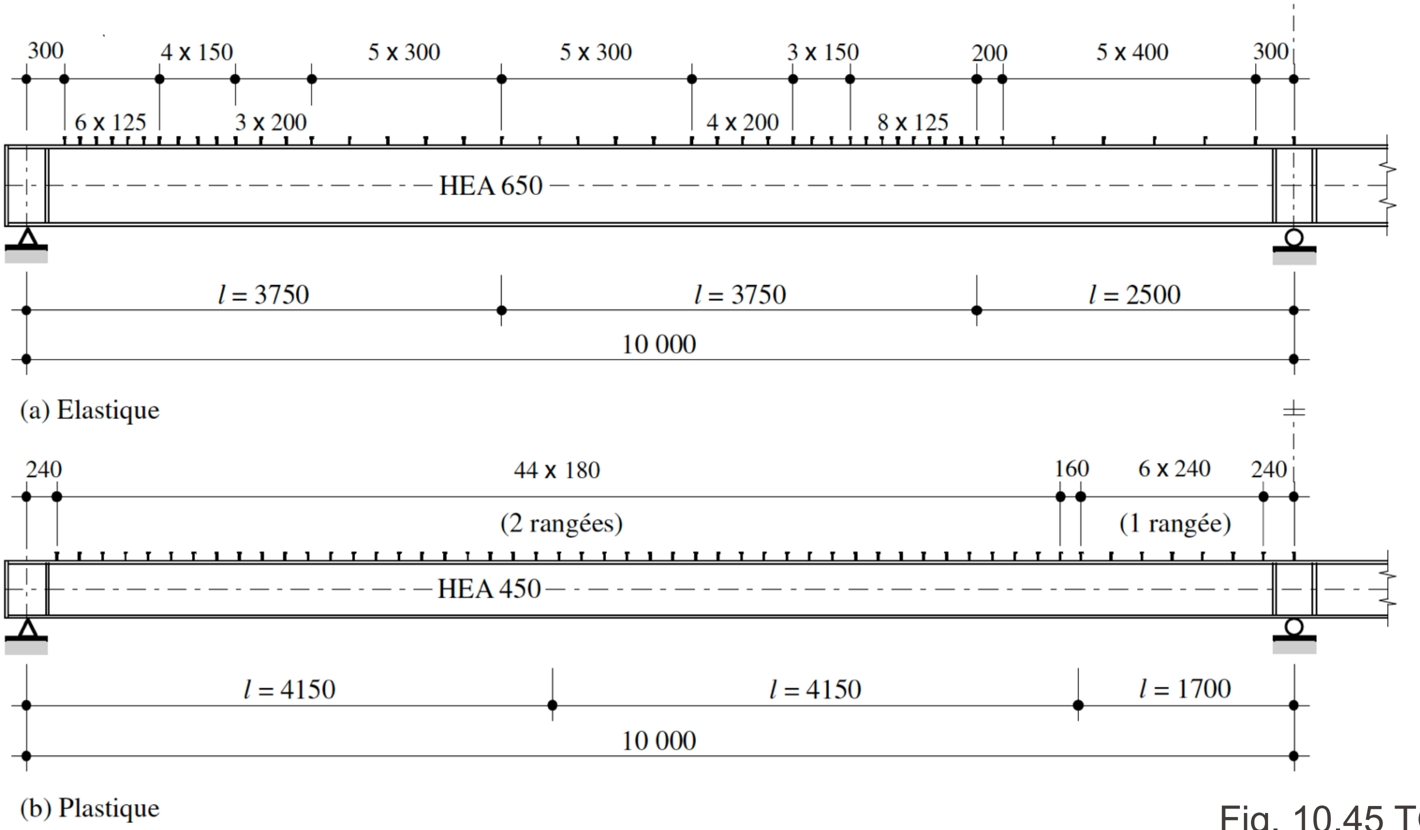
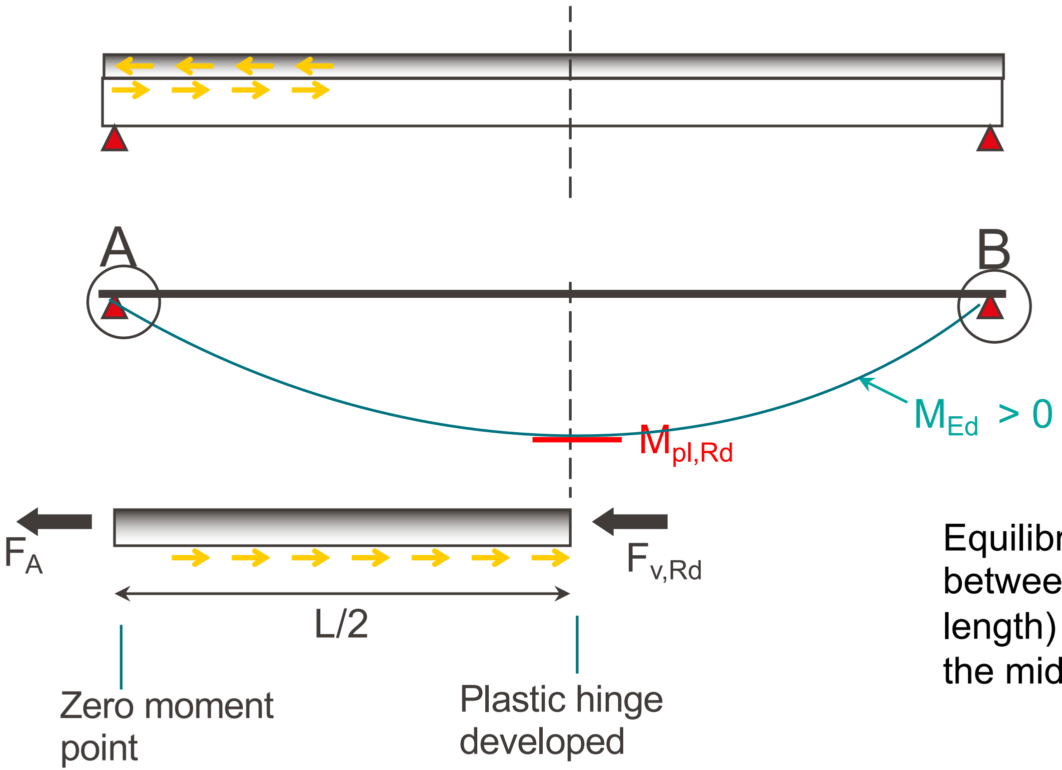



Fig. 10.45 TGC11

# Plastic calculation of the connection

Valid for beams with a cross-section class 1 or 2, justified for structural safety by a plastic cross-section calculation ($M_{Ed} \leq M_{pl,Rd}$ )



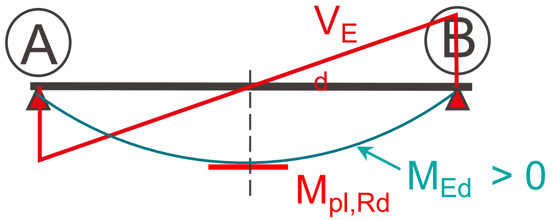

Equilibrium of the concrete block between A and mid-span (critical length) assuming $M_{Ed} = M_{pl,Rd}$ in the mid-span section

# Plastic calculation of the connection



- At the point of zero moment (i.e. on a support for a simple beam)

$$F_A = 0 \text{ (ou } F_B = 0)$$




- Equilibrium of the concrete block :

$$F_{V,Rd} - F_A = F_{V,Rd} \leq v_{pl,Rd} \cdot \frac{L}{2} \rightarrow N_{connect} \geq \frac{F_{V,i,Rd}}{P_{pl,Rd}}$$

with $N_{connect}$ to be distributed over the length of the concrete block (L/2)

- Shear resistance in span regions

$$F_{V,i,Rd} = \frac{0.85 f_{ck}}{\gamma_c} b_{eff} \cdot h_c$$ if neutral axis (p.n.a.) in the profile

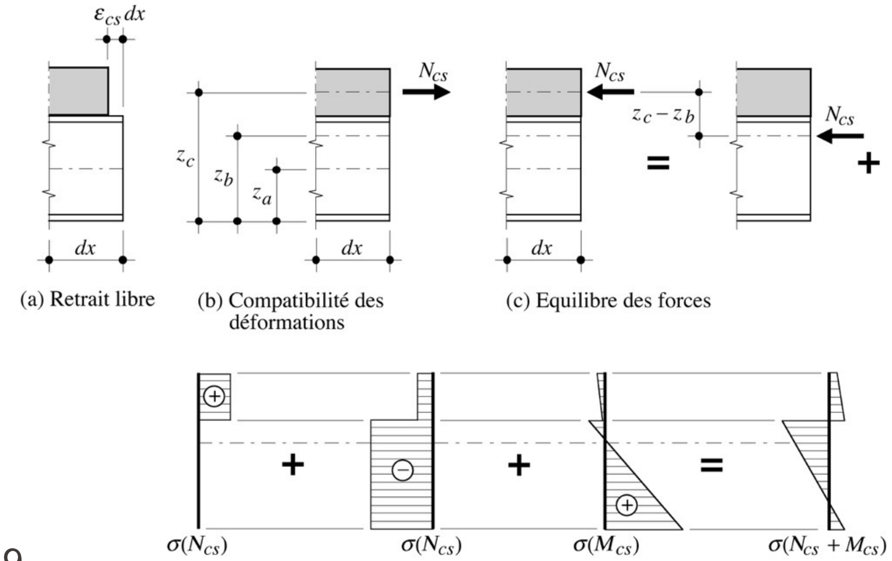
$$F_{V,i,Rd} = \frac{0.85 f_{ck}}{\gamma_c} b_{eff} \cdot x = \frac{f_y}{\gamma_{M1}} A_a$$ if neutral axis in the slab

# Continuous beam on 3 supports, several sections

# End zones: anchorage for forces due to shrinkage

- Building : $\varepsilon_{cs}(\infty) = 0.5‰$
- Bridge : $\varepsilon_{cs}(\infty) = 0.25‰$

$$N_{cs,Ed} = \gamma_G \cdot \varepsilon_{cs,\infty} \cdot E_{cs} \cdot A_c \qquad M_{cs,Ed} = N_{cs,Ed} \cdot \left(h - \frac{h_c}{2} - z_b\right)$$




(a) Retrait libre (b) Compatibilité des déformations (c) Equilibre des forces

(d) Contraintes

TGC 10 fig. 5.39

Axial force at end to anchor $F_{vs}$ :

$$F_{vs} = \sigma_{ag,s} \cdot A_a \text{ ou } \sigma_{c,s} \cdot A_c$$

# End zones: anchorage for forces due to shrinkage

- See TGC 11 fig. 10.32, especially for bridges (often neglected in buildings)
- End axial force to be anchored $F_{vs}$

$$F_{vs} = \sigma_{ag,s} \cdot A_a = A_a \left[ \frac{N_{cs}}{A_b} + \frac{M_{cs}}{I_b} (z_b - z_a) \right]$$

- Triangular load distribution on $x_s$, max at the end:

$$v_s = \frac{2F_{vs}}{x_s}$$

- Introduction length : $x_s = \min(b_{eff}; \frac{L}{10})$

# Constructive provisions for the connection, rules for positioning studs SIA 264 §7.1

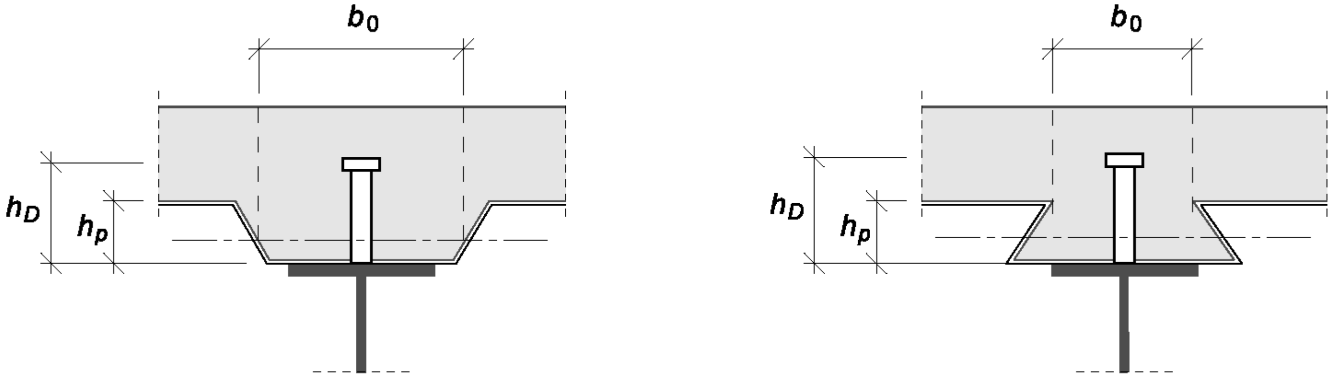
- Longitudinal connector spacing
  - Minimum: $e_1 \geq 5d$
  - Maximum, to ensure mixed behaviour between steel and concrete: $e_{1,\text{max}}$ = min (800 mm; $6 \cdot t_{slab}$)
  - Maximum, to be able to assign a class 1 or 2 to the compressed steel upper sole : $e_{1,max} = 22t_f\sqrt{235/f_y}$
- Transverse connector spacing
  - Minimum: $e_2 \geq 3.5d$
- Net distance between connector and edge of compressed steel base less than : $e_D = 9t_f\sqrt{235/f_y}$

# Resistance connection, special features (TGC11 §10.5.6)

- Influence of the presence of a profiled sheet parallel to the beam :

$P_{Rd}$ must be multiplied by $\alpha_L$: $$\alpha_L = \frac{0.6 b_0}{h_p}\left(\frac{h_D}{h_p} - 1\right) \leq 1.0$$

- Cross-sections: (TGC 11 fig. 10.39)



# Resistance connection, special features

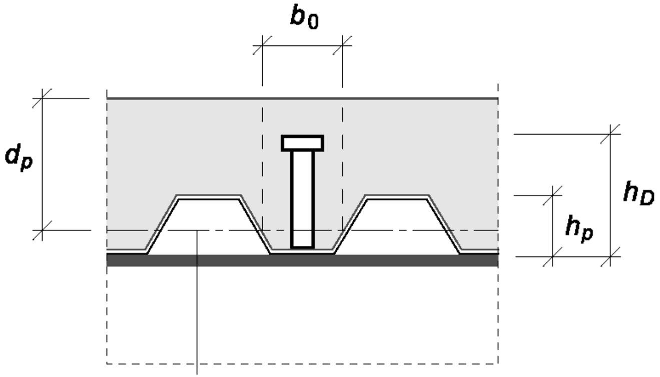


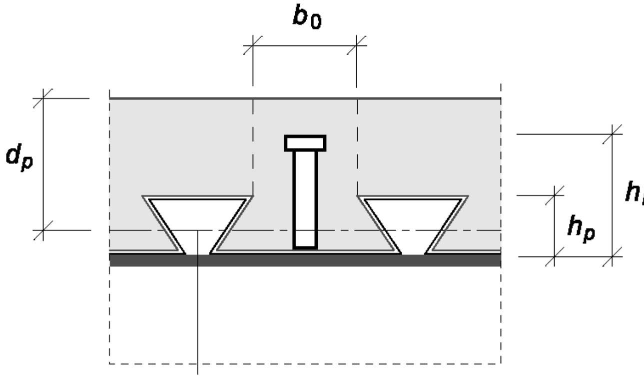
- Influence of the presence of a profiled sheet perpendicular to the beam:

$P_{Rd}$ must be multiplied by $\alpha_t$: $$\alpha_t = \frac{0.7 b_0}{\sqrt{N_r} h_p}\left(\frac{h_D}{h_p} - 1\right)$$

With $N_r$= number of studs per rib

- Longitudinal sections: (TGC 11 fig. 10.39)



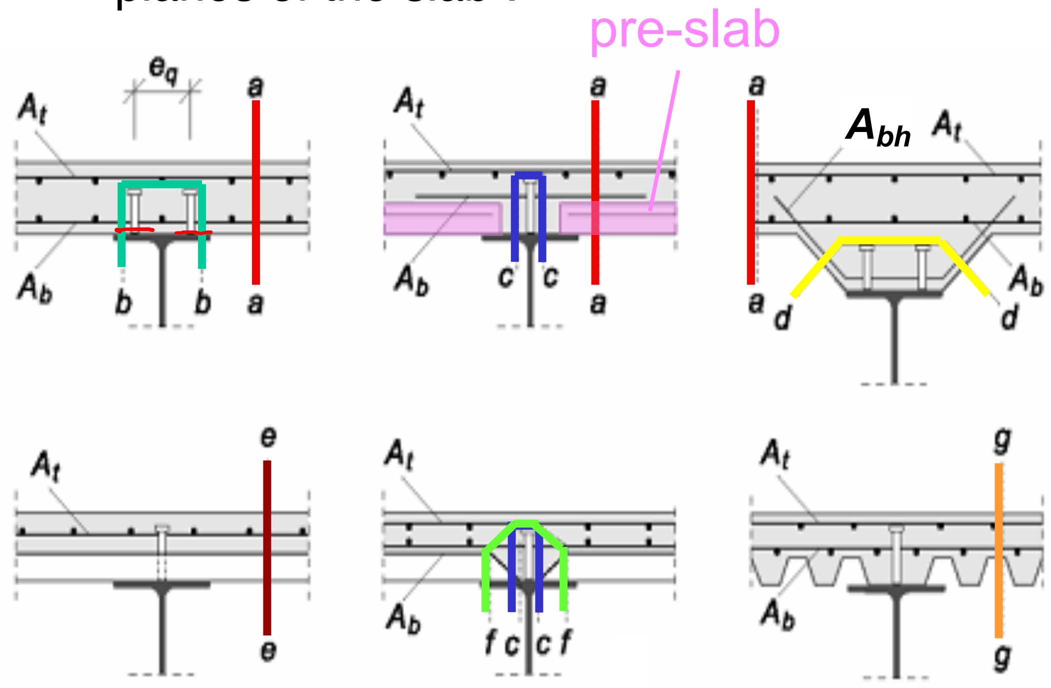



# Longitudinal shear

# Longitudinal shear in the slab (TGC11 §10.5.7)

- Checking the transverse reinforcement passing through the sheared planes of the slab :

SIA 264 §5.1.4.8



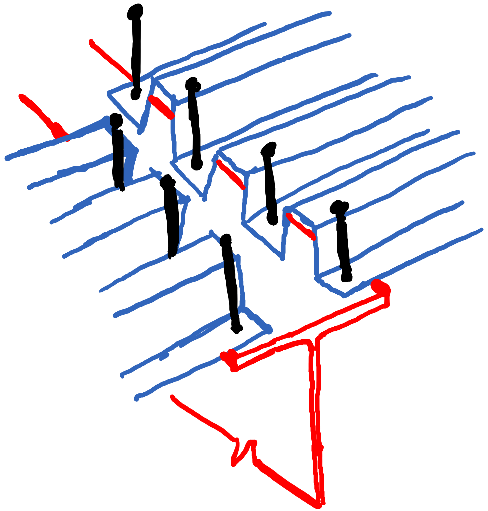

| Typ | $A_e$ | $L_c$ |
|---|---|---|
| a – a | $(A_b + A_t)$ | h |
| b – b | $2\,A_b$ | $2h_D + e_q + 2d_k$ |
| c – c | $2\,A_b$ | $2h_D + d_k$ |
| d – d | $2\,A_{bh}$ | Case by case |
| e – e | $A_t$ | $h_c$ |
| f – f | $2\,A_b$ | Case by case |
| g – g | $(A_b + A_t)$ | $h_c$ |

Fig. 10.41 - TGC 11

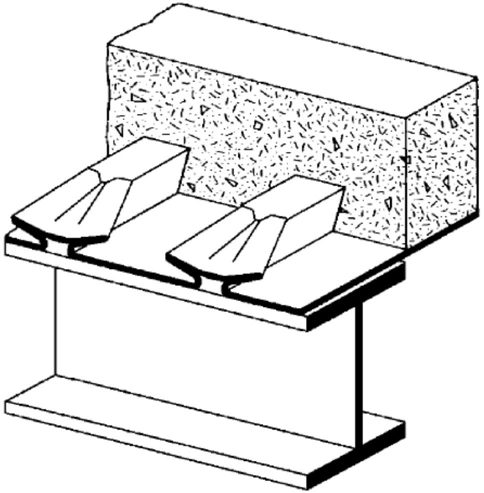
# Longitudinal shear, interrupted sheets on beam

- Interrupted perpendicular ribs at the top flange of the beam, sheet metal

  - welded with studs (through profiled sheet metal)



  - not connected to the beam, but anchored (anti-slip)



# Longitudinal shear in the slab



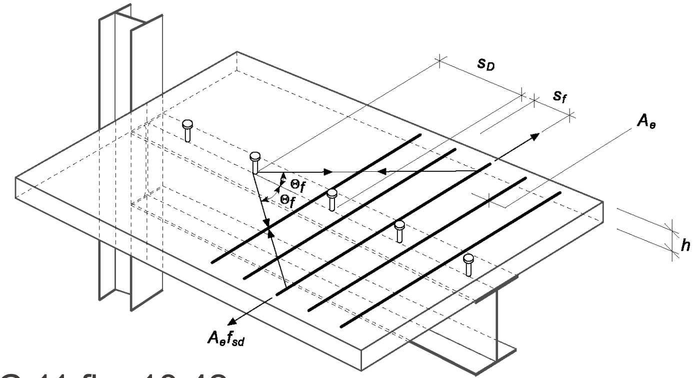
- Truss analogy
- Contribution of the slab transverse reinforcement $v_{Rd}$

$$V_{Rd} = \frac{A_e}{s_f} f_{sd} \cot(\theta_f)$$

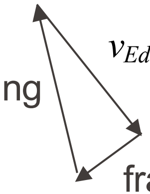
Transverse reinforcement in tension

$$V_{Rd} \leq k_c f_{cd} L_c \sin(\theta_f) \cos(\theta_f)$$

Limitation due to failure of the compressed concrete connecting rod ($k_c = 0.55, f_{cd} = f_{ck}/\gamma_c$)




TGC 11 fig. 10.42
SIA 264 fig. 4




Connecting rod angle:
- If concrete - : $25° < \theta_f < 45°$
- If concrete + : $35° < \theta_f < 45°$

# Longitudinal shear of slab with sheet metal

- Sheet metal with continuous ribs perpendicular to the beam, addition of sheet metal contribution

$$\nu_{Ed} \leq v_{Rd} + v_{pd}$$

$$\nu_{pd} = \frac{A_p \cdot f_{yp}}{\gamma_{ap}}$$

$v_{Rd}$ contribution of the reinforcement

$v_{pd}$ contribution of profiled sheet

$f_{yp}$ yield strength of sheet steel

$A_p$ cross-section of profiled sheet per unit width

$\gamma_{ap}$ = 1.05 (sheet metal)

- Interrupted at the upper flange of the beam, but welded with studs → see appendix

TGC 11 §10.5.7
SIA 264 §5.1.4.8

# Partial connection

TGC 11 §10.5.5

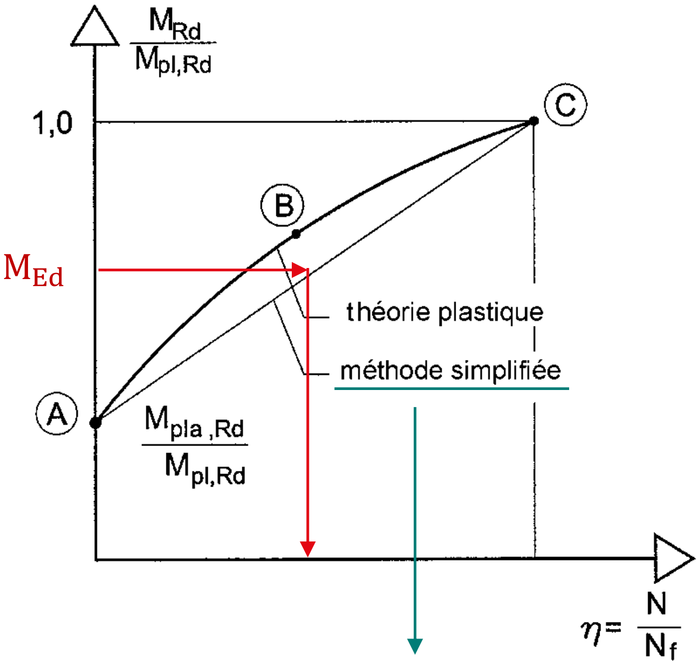
# Partial connection

Partial connection: Connection with a reduced number of connectors that does not allow the full plastic resistance of the composite beam to be achieved

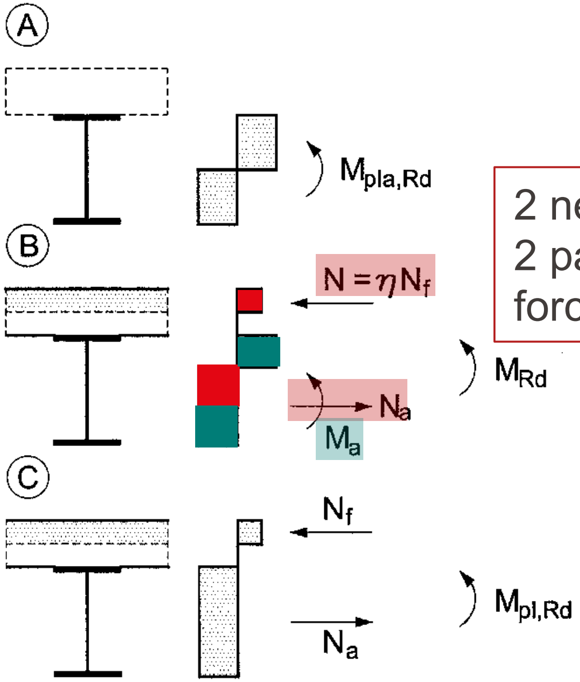
- Plastic calculation, ultimate strength of the composite beam limited by the connection
- Applicable when calculating composite beams for buildings under M+, with flexible connectors
- for beams with a span of 5 to 10 m, the degree of connection ($N_{partial}/N_{total}$ ) must remain greater than 40%

# TGC 11, fig. 10.34 Partial connection principle





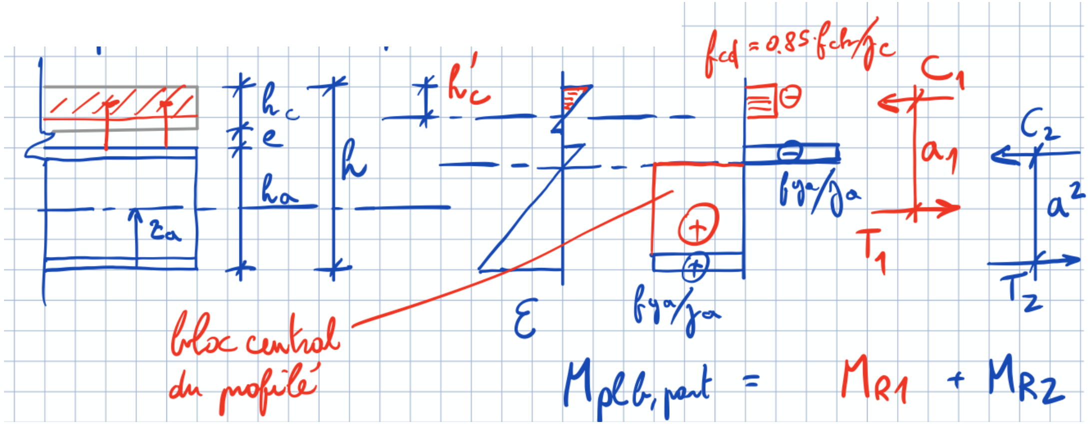

$$M_{Ed} = M_{Rd} = M_{pla,Rd} + \frac{(M_{pl,Rd} - M_{pla,Rd})N}{N_f}$$




2 neutral axes
2 pairs of
forces

*N*: nb of connectors
$N_f$ : nb of connectors required for total connection

# Partial interaction analysis, A-B-C curve




- Si $A_a > A_c/n_{pe}$, a.n. dans poutre.
- Par définition : $C_1 = N_i \cdot P_{Rd} = h'_c \cdot f_{cd} \cdot b_{eff}$
  et $C_1 \equiv T_1$

$N_i$ = nb. de goujons de l'appui à $M_{max}$

$$h'_c = \frac{N_i \cdot P_{Rd}}{f_{cd} \cdot b_{eff}} = \frac{A_c \cdot \cancel{f_{cd}} \cdot N_i \cdot \cancel{P_{Rd}}}{\underbrace{N_f \cdot \cancel{P_{Rd}}}_{\text{conn. tot. } A_c \cdot f_{cd} = N_f \cdot P_{Rd}} \cancel{f_{cd}} \cdot b_{eff}} = \frac{A_c}{b_{eff}} \cdot \frac{N_i}{N_f} \qquad (10.69)$$

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# Partial interaction analysis, A-B-C curve



- On déduit donc $M_{R1}$ :

$$M_{R1} = C_i \left(h - z_a - h'_c/2\right) = N_i \cdot P_{Rd} \cdot \left(h - z_a - h'_c/2\right)$$

- Note : pour caractéristiques plastiques en section (Tab. 10.23) remplacer $h_c$ par $h'_c$, et $A_c$ par $A'_c = b_{eff} \cdot h'_c$

Interaction formula N+M:
SIA 263, equ. (45)

$$M_{ply,N,Rd} = M_{R2} = M_{ply,Rd} \cdot \xi \cdot (1 - n) \leq M_{ply,Rd}$$

Dans notre cas : $N_{Ed} = T_1/\gamma_a = N_i \cdot P_{Rd}/\gamma_a$

$N_{ply,Rd} = N_f \cdot P_{Rd}/\gamma_a$ cas conn. totale.

$M_{ply,Rd} = M_{pla}/\gamma_a$ $M_{pl}$ résistant du profilé

- Finalement on obtient :

$$M_{plb,part,Rd} = M_{R1} + M_{R2} = N_i \cdot P_{Rd} \left(h - z_a - \frac{h'_c}{2}\right) + M_{pla}/\gamma_a \cdot \xi \cdot \left(1 - \frac{N_i}{N_f}\right)$$

comme $h'_c = \frac{A_c}{b_{eff}} \frac{N_i}{N_f}$, il s'agit d'une équ. du 2ème degré.

# Design method, simplified curve = straight line



- Number of studs required: $$N_{nec} \geq \frac{M_{Ed} - \frac{M_{pl,a}}{\gamma_a}}{\frac{M_{pl,b}}{\gamma_a} - \frac{M_{pl,a}}{\gamma_a}} N_f$$

  (for $M_{Ed} < M_{plb,Rd}$)

- Laminated beams, limited degree of connection:

$L_e \leq 25$ m: $$\frac{N}{N_f} \geq 1 - \frac{355\ \mathrm{N/mm^2}}{f_y}(0.75 - 0.03\ L_e) \geq 0.4$$

$L_e > 25$ m: $$\frac{N}{N_f} \geq 1$$

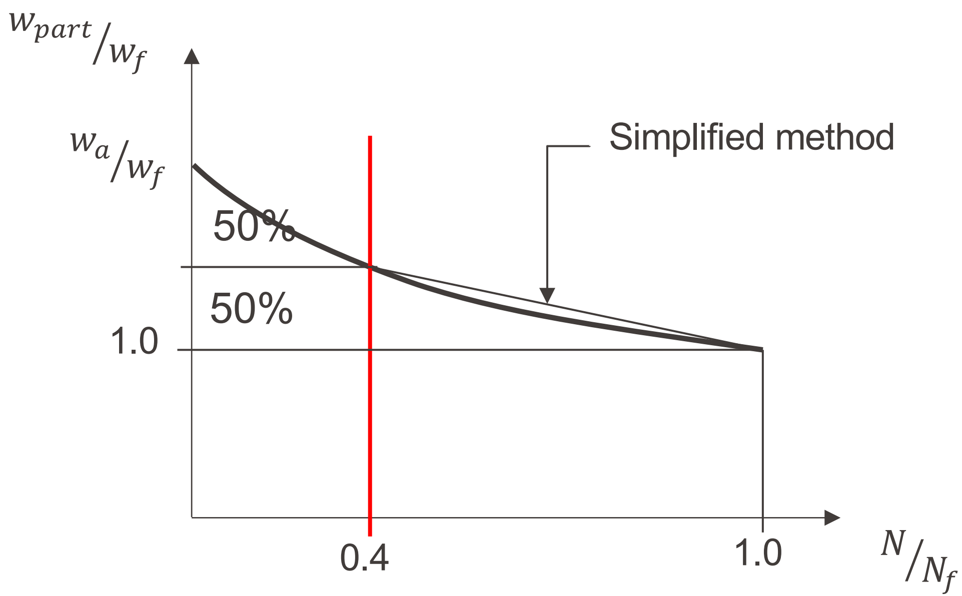
$L_e$ distance between zero moment points [m]

- And at ELS, for calculating deflections?

# Calculating deflections

- Increased deflection due to sliding at the interface
- Estimation using a simplified method similar to the previous one (for strength):

$$\mathrm{w_{part}} = \mathrm{w_f} + 0.5(\mathrm{w_a} - \mathrm{w_f})\left(1 - \frac{\mathrm{N}}{\mathrm{N_f}}\right) \text{ si } \frac{\mathrm{N}}{\mathrm{N_f}} \geq 0.4$$



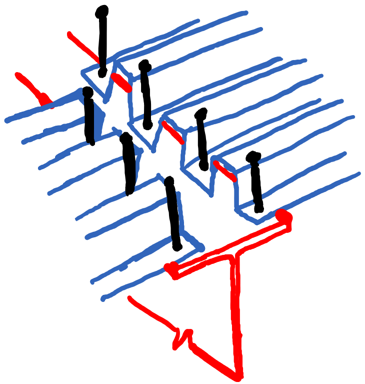
# Appendices

# Longitudinal shear with interrupted sheets

- Perpendicular ribs interrupted at the upper flange of the beam, but welded with studs (through the profiled sheet)

$v_{pd}$ contribution of welded studs/profile plate

$P_{pb,Rd}$ resistance to lateral pressure of the sheet



$$\mathrm{v_{pd}} = \frac{\mathrm{P_{pb,Rd}}}{\mathrm{s_d}} \leq \frac{\mathrm{A_p} f_{yp}}{\gamma_{ap}}$$

$$\mathrm{P_{pd,Rd}} = \mathrm{k_\varnothing\, d_{d0}\, t}\, f_{yp} \frac{1}{\gamma_{ap}}$$

$$\mathrm{k_\varnothing} = 1 + \mathrm{a/d_{d0}} \leq 6.0$$

| | |
|---|---|
| $f_{yp}$ | yield strength of sheet steel |
| $A_p$ | cross-section of profiled sheet per meter of width |
| $d_{d0}$ | diameter of stud weld |
| $t$ | sheet thickness |
| $a$ | distance between the centre of the stud and the edge of the metal sheet |
| $s_d$ | Longitudinal stud spacing |