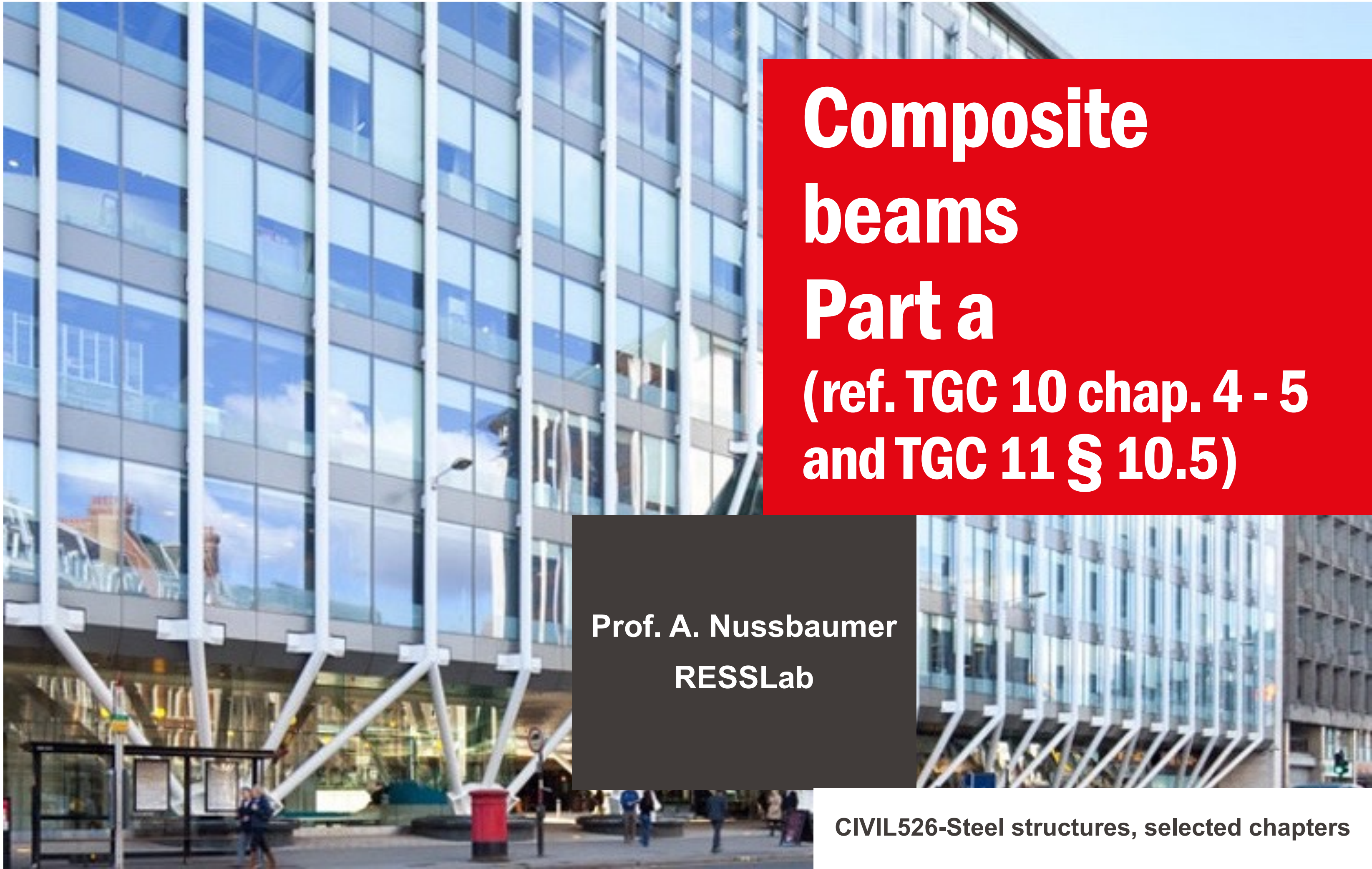


Composite beams Part a (ref. TGC 10 chap. 4 - 5 and TGC 11 § 10.5)

Prof. A. Nussbaumer
RESSLab

CIVIL526-Steel structures, selected chapters

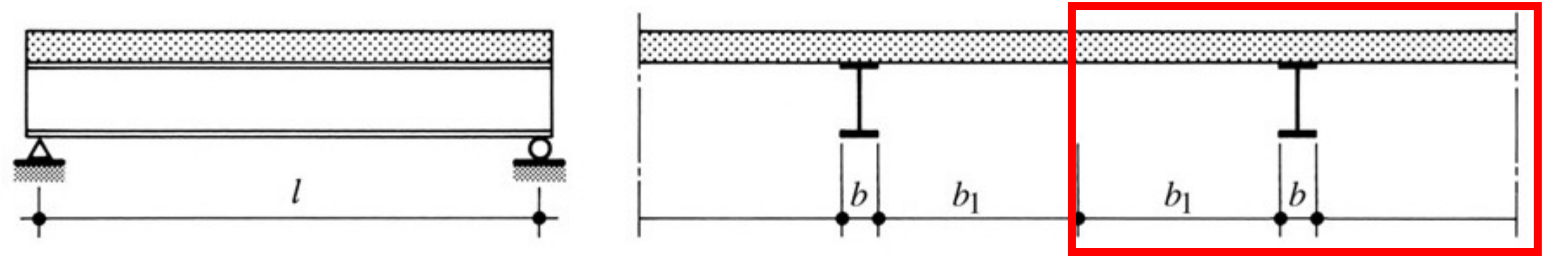
Overall content

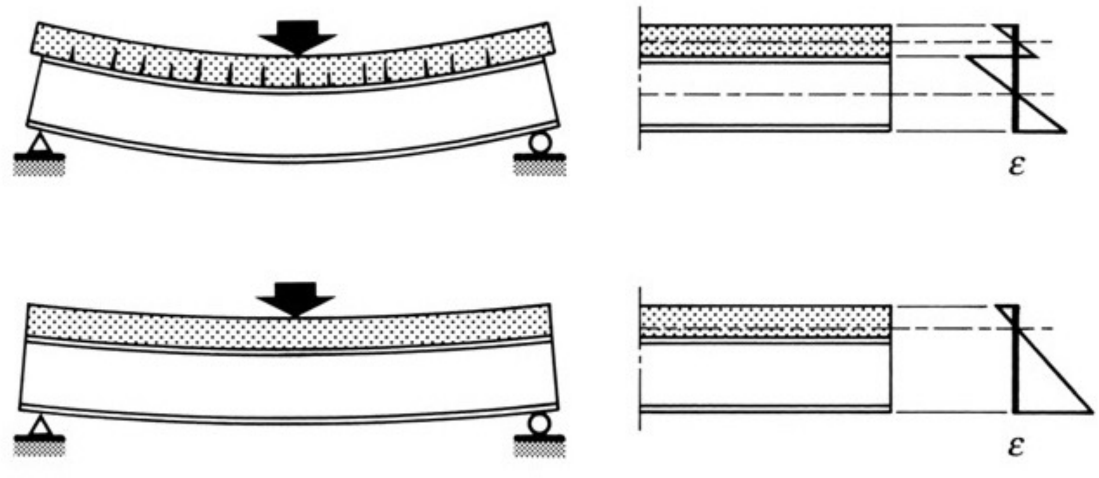
- Introduction (recall)
- Section strength
- Structural analysis
- Structural verification, ELU
- Serviceability check, ELS
- Connection

Contents part a

- Introduction (recall)
- Section strength
- Appendices

Introduction: Composite beam





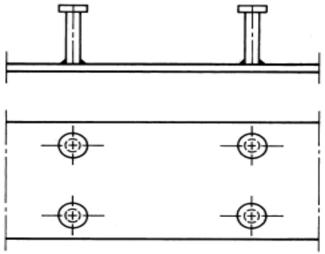
(a) Sans liaison.
= non-composite behaviour of the section

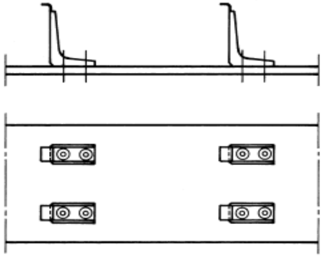
(b) Avec liaison.
= composite behaviour of the section

(b = binden, Verbund)

Introduction: Types of connection

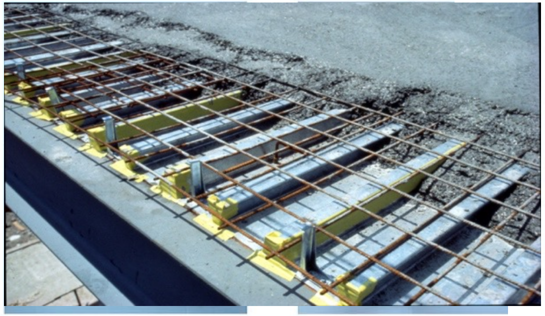
Composite elements need a connection between steel and concrete to work together



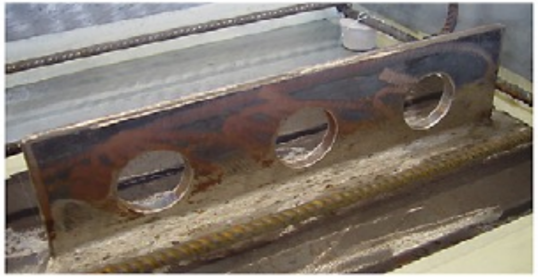


The systems most commonly used today

Headed studs

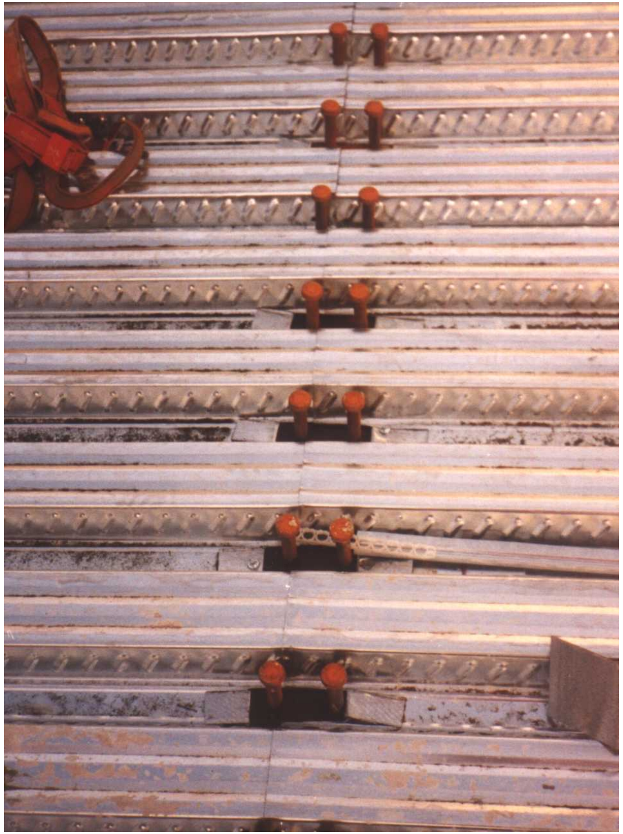


Hilti studs



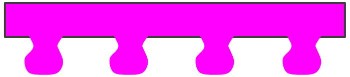
Perfobond connectors

Introduction: Studs with profiled sheeting

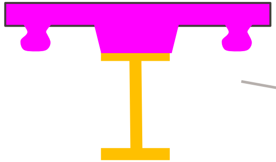


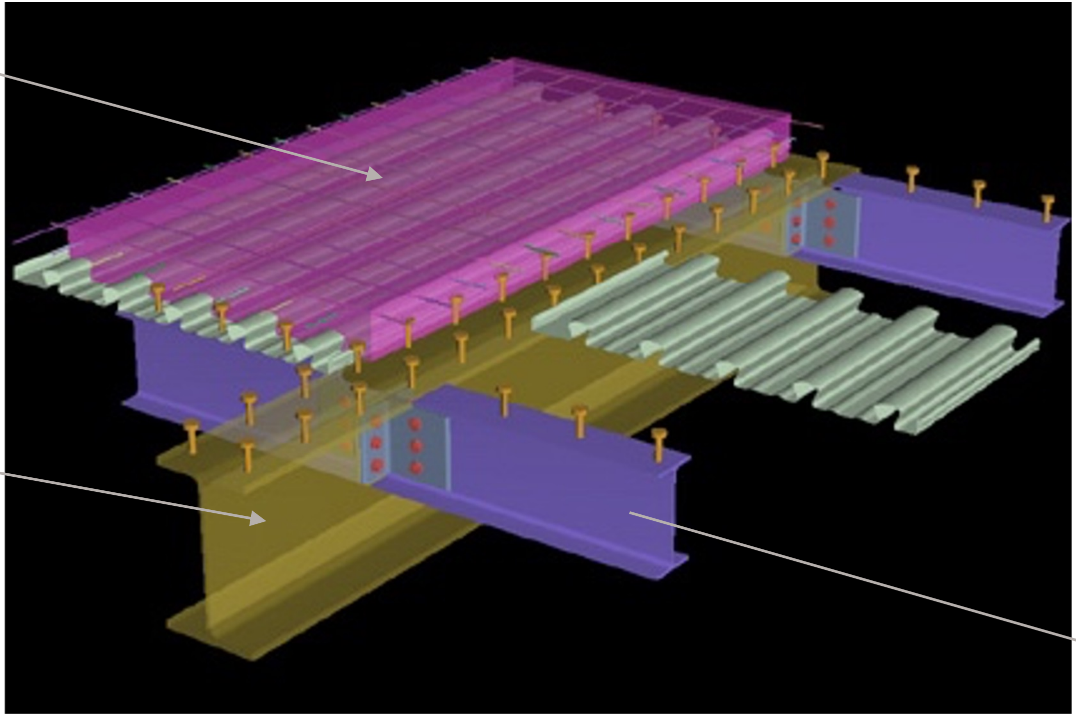
Introduction: Influence of profiled sheeting direction

Composite slab

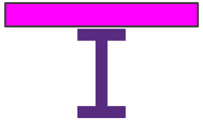


Main beam (composite)





2nd beams (composite)



Introduction: Advantages of composite construction

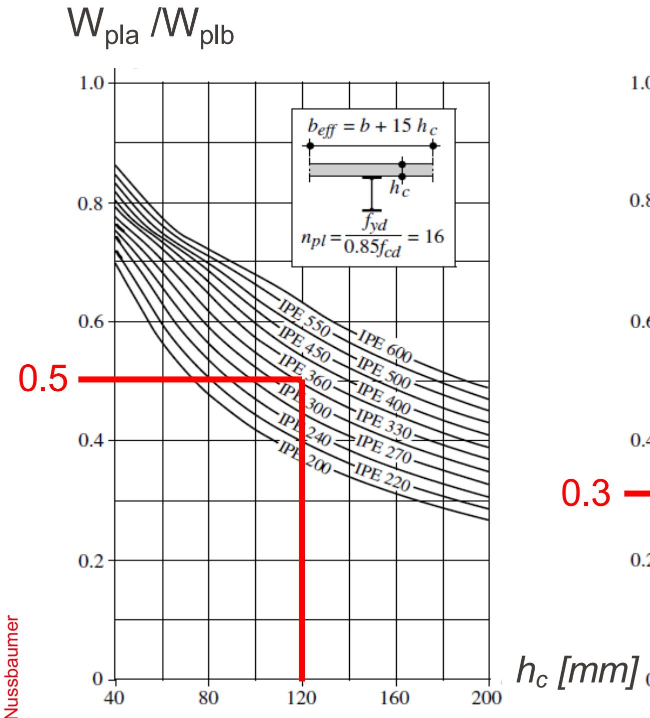
Stronger, stiffer beams than steel alone

- Steel weight reduced by 30 to 50%.
- Reduced height of the beam
- Lighter construction
- Improved fire resistance and vibration characteristics

Composite slabs

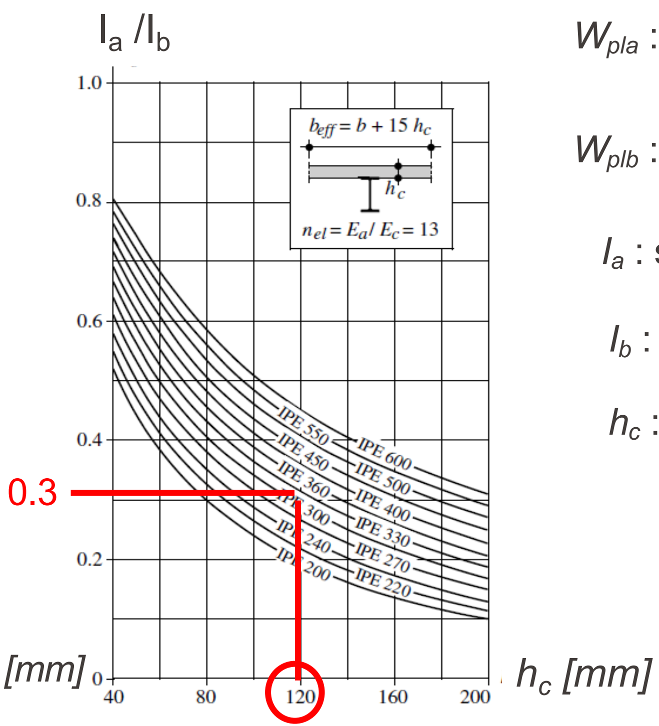
- Sheets are used as formwork and work platforms (dry worksite)
- Profiled sheeting stabilise the steel beam
- Improved fire resistance

Benefits, TGC11 fig. 10.20



Resistance

2 times



Stiffness

3 times

W_{pla} : steel plastic section modulus

W_{plb} : composite plastic section modulus

I_a : steel moment of inertia

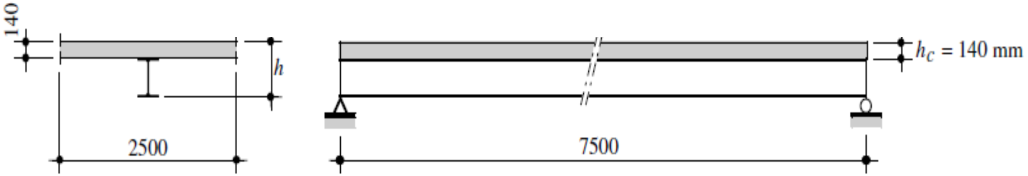
I_b : composite moment of inertia

h_c : height of the concrete slab

Example: $h_c = 120$
IPE 360

EPFL

Benefits, TGC11 fig. 10.21



Comparison	Comparaisons	No connection	With connection (studs)		
		Plastic design	Elastic design	Plastic design Full connection	Plastic design 40%
Height	Hauteur h [mm]	540	500	410	440
Section	Profilé	IPE 400	IPE 360	IPE 270	IPE 300
Section mass	Masse du profilé [kg/m]	66.3	57.1	36.1	42.2
Total stud nb	Nombre total de goujons (ø 19 mm)	—	13	25	12
Deflection due to permanent loads	Flèche due aux actions permanentes [mm]	10	12	33	24
Deflection due to creep	Flèche due au retrait ($\varphi_{cs,\infty} = 0.35 \cdot 10^{-3}$) [mm]	—	6	7	7
Deflection due to live load	Flèche due à la charge utile [mm]	8	3	6	10

Precamber (contreflèche)

Section strength

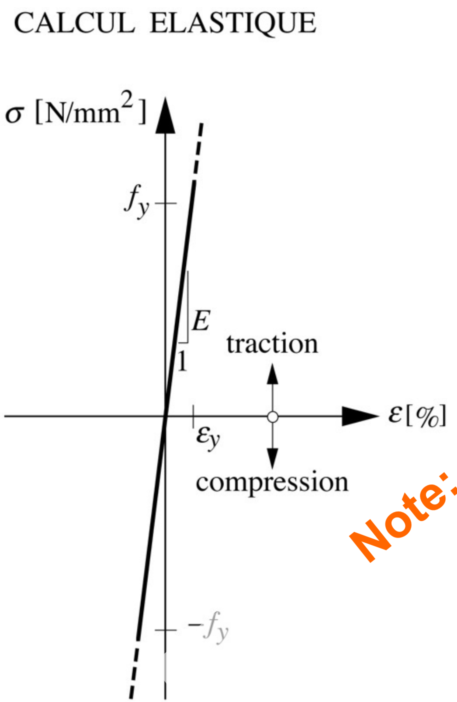
TGC 10 § 4.7.4

TGC 11 § 10.5.3

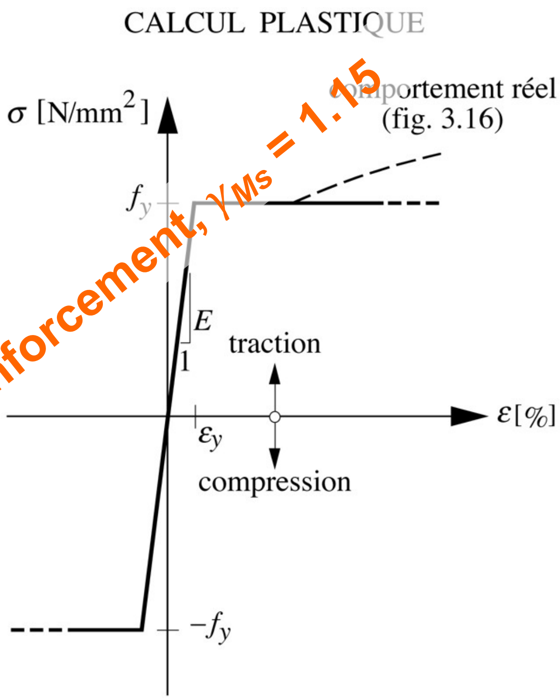
Characteristics of materials

Steel, as usual (figure 4.1: idealised behaviour law)

Resistance: Elastic design



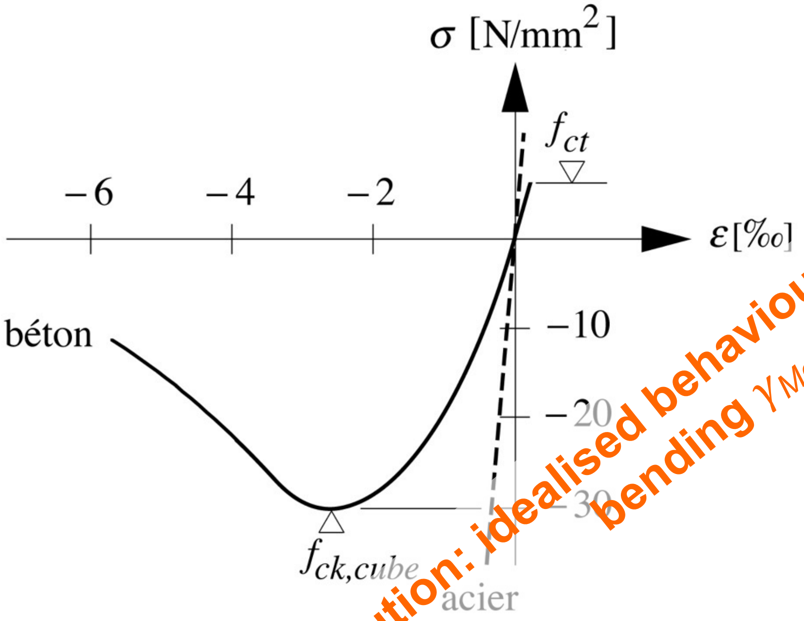
Plastic design



Note: for reinforcement, $\gamma_{Ms} = 1.15$

Characteristics of materials

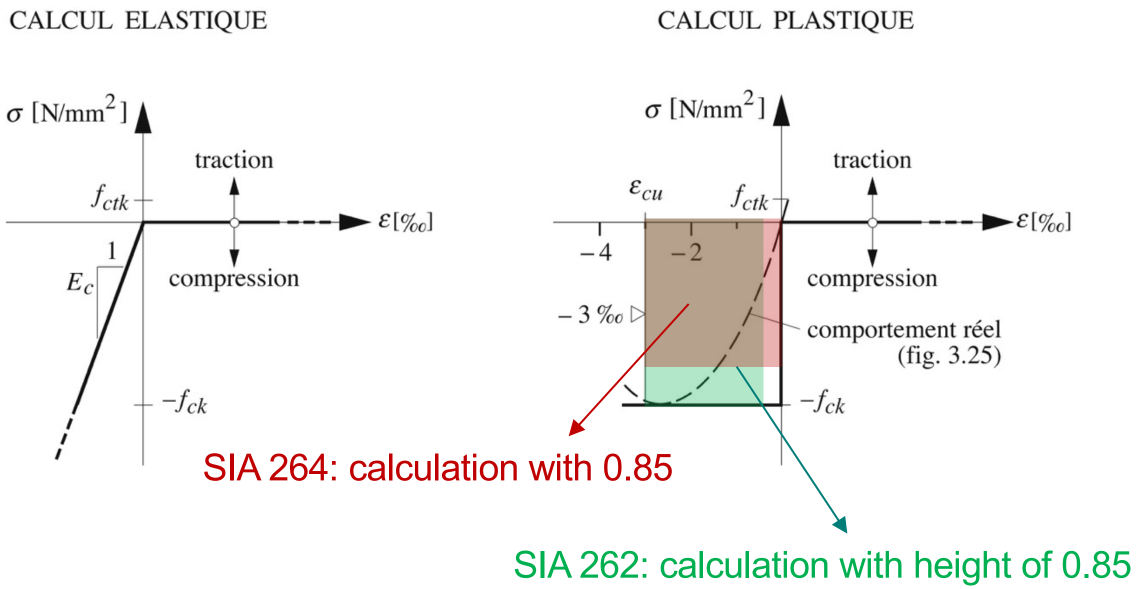
Concrete: TGC10, fig. 3.26 behaviour law and Tab. 3.27



Caution: idealised behaviour law for beam in bending $\gamma_{Mc} = 1.5$

Béton	f_{ck} [N/mm^2]	$f_{ck,cube}$ [N/mm^2]	f_{cd} [N/mm^2]	τ_{cd} [N/mm^2]
C 12/15	12	15	8	0.7
C 16/20	16	20	10.5	0.8
C 20/25	20	25	13.5	0.9
C 25/30	25	30	16.5	1.0
C 30/37	30	37	20	1.1

Reminder: concrete, idealized behaviour laws



For example:

C35/45 concrete

Propriété mécanique	Notation	Valeur	unité
valeur caractéristique en comprésion béton C35/45	$f_{ck,cylindre,28\ jours}$	35	N/mm^2
valeur moyenne en compression	$f_{cm}=f_{ck}+8$	43	N/mm^2
Valeur de dimensionnement	$f_{cd}=f_{ck}/\Upsilon_c$	23.3	N/mm^2
Valeur moyenne en traction	fctm	3.2	N/mm^2
Module d'élasticité moyen	$E_{cm}=K_E\ .\ (f_{cm})^{1/3}$	35000	N/mm^2

Reminder: behaviour under bending moment M+

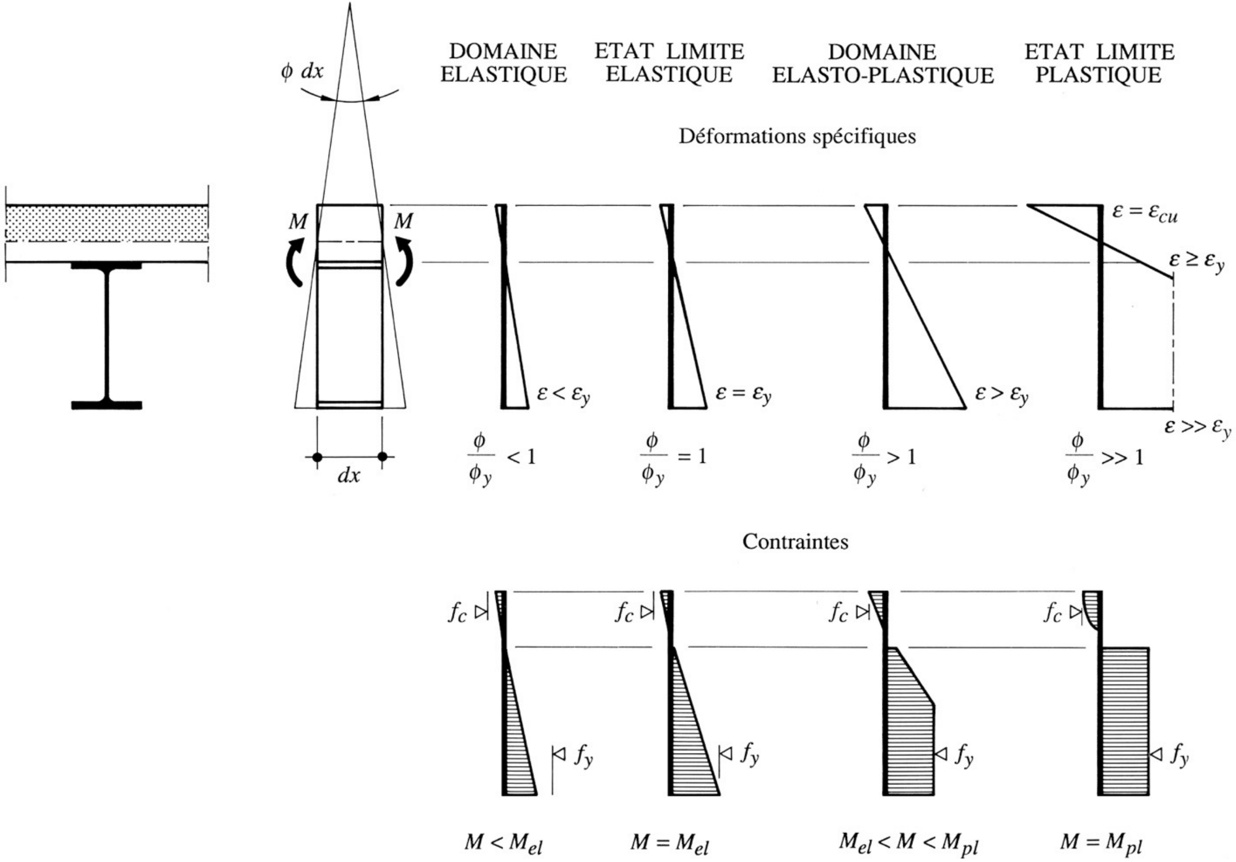


Fig. 4.54 - TGC 10

Sizing method

1. Determining the **section class**:
   - Elastic or plastic resistance check of the section?
2. Determination of internal forces (elastic or plastic, redistribution)
3. Calculation of composite **mechanical properties:**
   - Slab in compression: concrete resists and neglect reinforcement
   - Slab in tension: cracked (and neglected) concrete and reinforcement considered
   - Elastic or plastic calculation ?
   - How long will the charges last ?
   - Position of the neutral axis (in the slab or in the steel beam) ? $z_{el,b,i}$, $z_{pl,b}$
   - Section modulus: $I_{b,i}$, $W_{el,b,i}$, $W_{pl,b}$
4. sections checks

5) What is the equivalence coefficient n_{pl} ?

A. Reduction coefficient of cylinder strength of concrete

B. Transformation coefficient of modulus E_a / E_c

C. Strength transformation coefficient for concrete into steel

D. Yield strength transformation coefficient for steel into concrete

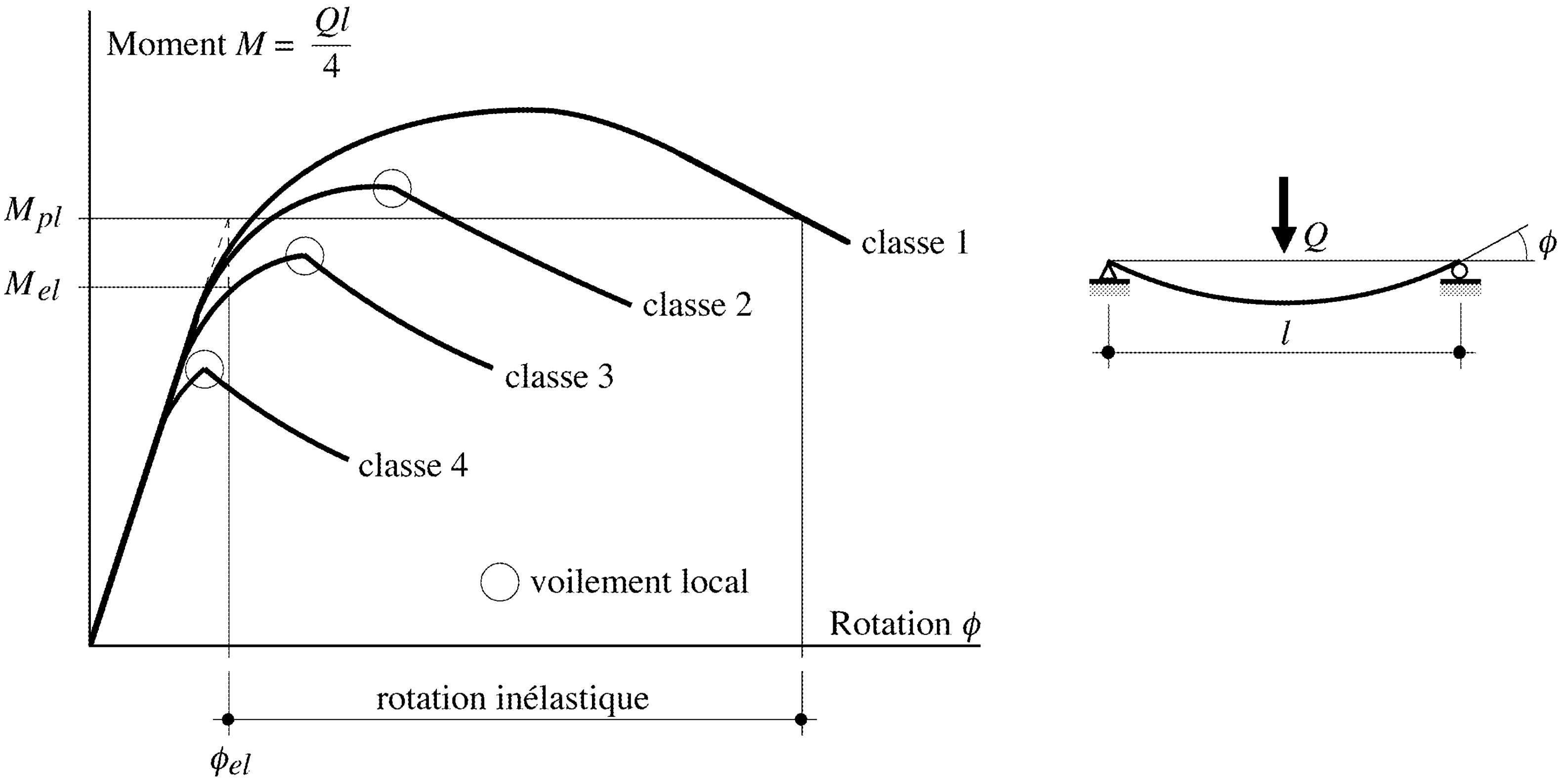
Elastic calculation: Effects of concrete properties

	Equivalence coefficient
Short term $E_c = E_{c0} = E_{cm}$ short-term value of the modulus of elasticity	$n_{el,0} = \frac{E_a}{E_c} \approx 6$ Short-term actions
Creep (Eurocode formula) $E_{cm}(t) = \left(\frac{f_{cm}(t)}{f_{cm}}\right)^{0.3} E_{cm}$ f_{cm}: average compressive strength Swiss simplification (SIA 264 §3.5.2):	$n_{el,\infty} \approx 3\, n_{el} \approx 18$ Long-term actions
Shrinkage (depending on the case, often neglected in buildings, to be taken into account in bridges) Swiss simplification : $E_c = E_{cs} = \frac{E_{cm}}{2}$	$n_{el,s} \approx 2\, n_{el} \approx 12$ Shrinkage, settlements

Elastic calculation: resistant section and coeff. of equivalence according to load case considered

Type of action	Resistant section	Equiv. coeff.
Dead weight (steel profile, concrete)	Steel + static mounting system	-
Reaction of props	Mixed + final static system	$n_{el,\infty}$
Permanent loads (screed, finishes, insulation)	Mixed + final static system	$n_{el,\infty}$
Live loads (short-term)	Mixed + final static system	$n_{el,0}$
Live loads (long-term)	Mixed + final static system	$n_{el,\infty}$
Shrinkage	Mixed + final static system	$n_{el,s}$

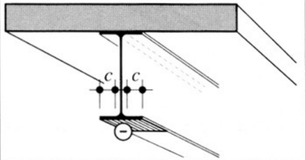
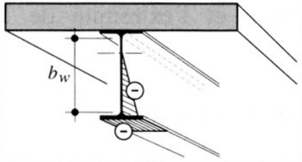
TGC 11, fig. 10.27: Composite section class



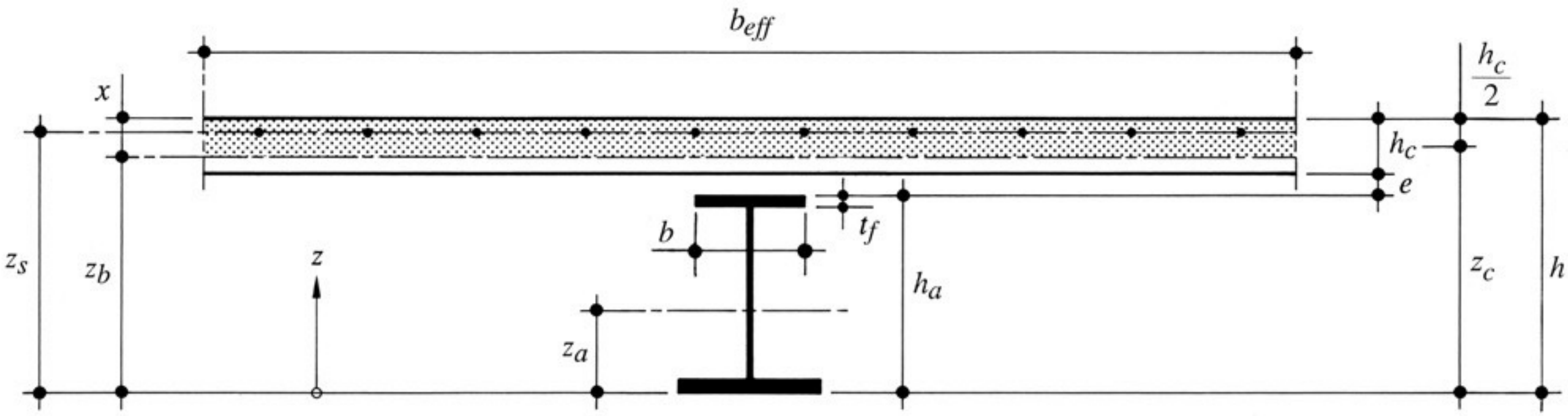
TGC 11, Tab. 10.43: Composite section class

Same as for a steel section except:

- Under M-, web often fully compressed (neural axis high, or in concrete)
- Flange compressed under the slab is always class 1 (buckling and tilting prevented). Condition: connection complying with the rules for geometric positioning of studs on flanges (SIA 264 4.2.2.3). Other rules for composite columns
- Plastic strength design possible if class 1 or 2 for flange and web.

Elément comprimé		Classe de section 3	Classe de section 2	Classe de section 1
Aile comprimée		$\frac{c}{t_f} \leq 14 \sqrt{\frac{235}{f_y}}$	$\frac{c}{t_f} \leq 10 \sqrt{\frac{235}{f_y}}$	$\frac{c}{t_f} \leq 9 \sqrt{\frac{235}{f_y}}$
Ame fléchie		$\frac{b_w}{t_w} \leq 42 \sqrt{\frac{235}{f_y}}$	$\frac{b_w}{t_w} \leq 38 \sqrt{\frac{235}{f_y}}$	$\frac{b_w}{t_w} \leq 33 \sqrt{\frac{235}{f_y}}$

Notation

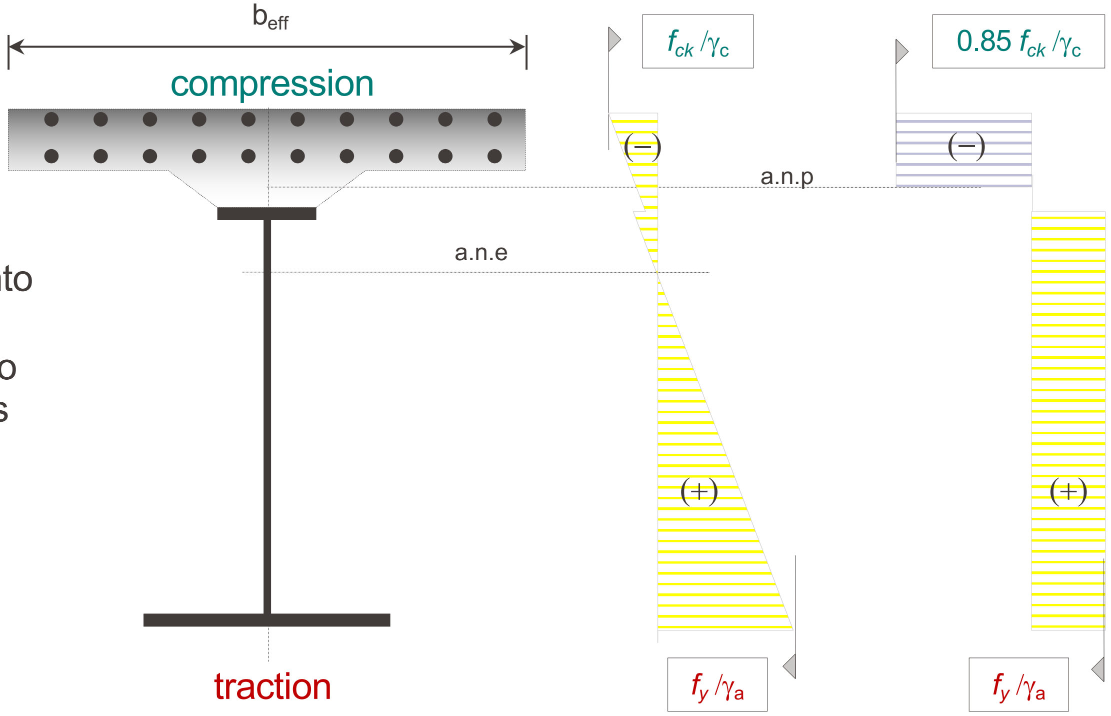


Position of the referenced neutral axes made wrt underside of the bottom flange of the composite beam

Resistance calculation assumptions

- **Participating** (or effective) **width** of the concrete slab?
  - Determination using the shear lag model
  - SIA 262 §4.1.3.3 or TGC 10 p.209
- Whether or not reinforcement is taken into account depends on the **moment sign** :
  - Same model as above for effective width
  - Slab in compression: concrete resists, usually neglect reinforcement
  - Slab in tension: cracked (and neglected) concrete and reinforcement considered
- SIA 264 §3.5.1
  - f_{ck} between 20 and 50 $\mathrm{N/mm^2}$

Resistance under positive moment (slab in compression)



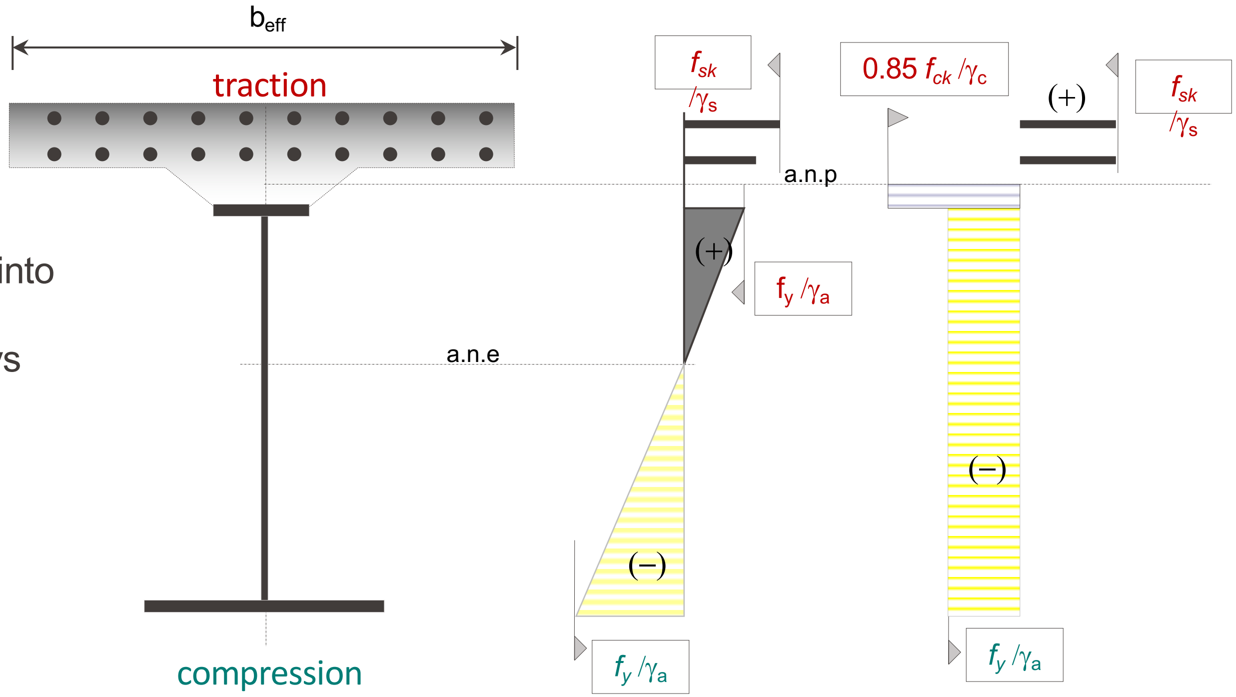
Rebars taken into account?

- Buildings: no
- Bridges: yes

Elastic resistance (for all classes)

Plastic resistance (class 1 and 2)

Resistance under negative moment (cracked slab)



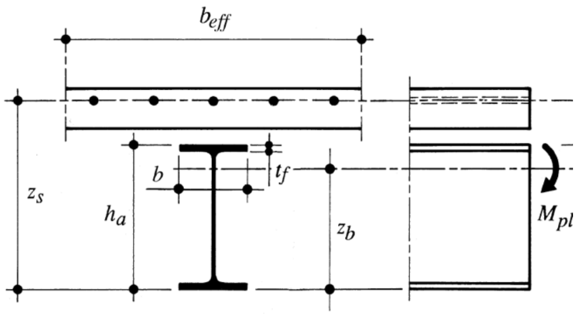
Rebars taken into account?

- Yes, always

Elastic resistance (for all classes)

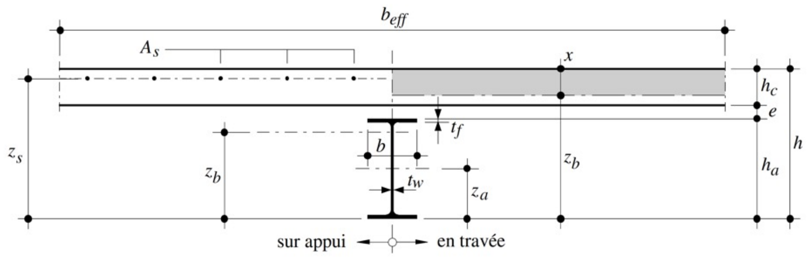
Plastic resistance (class 1 and 2)

Determination of section char.: Plastic calculation on support



Determination of section char.: Plastic calculation on support

TGC 11, tab. 10.22: ELASTIC char. of a composite section



Section	Axe neutre	Position de l'axe neutre et inertie de la section
En travée	Dans la dalle : $A_a\left(h - z_a - h_c\right) < \frac{A_c}{n_{el}}\frac{h_c}{2}$	$z_b = h - \frac{n_{el}\,A_a}{b_{eff}}\left[-1 + \sqrt{1 + \frac{2\,b_{eff}}{n_{el}\,A_a}\left(h - z_a\right)}\right]$ $I_b = I_a + A_a\left(z_a - z_b\right)^2 + \frac{1}{3}\frac{b_{eff}}{n_{el}}\left(h - z_b\right)^3$
	Dans le profilé métallique : $A_a\left(h - z_a - h_c\right) \ge \frac{A_c}{n_{el}}\frac{h_c}{2}$	$z_b = \frac{1}{A_a + \frac{A_c}{n_{el}}}\left[A_a\,z_a + \frac{A_c}{n_{el}}\left(h - \frac{h_c}{2}\right)\right]$ $I_b = I_a + A_a\left(h - z_a\right)^2 + \frac{1}{3}\frac{A_c}{n_{el}}h_c^2 - A_b\left(h - z_b\right)^2$
Sur appui		$z_b = \frac{1}{A_a + A_s}\left(A_a\,z_a + A_s\,z_s\right)$ $I_b = I_a + A_a\left(z_a - z_b\right)^2 + A_s\left(z_b - z_s\right)^2$

TGC 11, tab. 10.23: PLASTIC char. of a composite section

$Z_b = W_{pl,b}$

Section	Axe neutre	Position de l'axe neutre et module plastique de la section
En travée	Dans la dalle: $A_a \leq \frac{A_c}{n_{pl}}$	$z_b = h - \frac{n_{pl} \; A_a}{b_{eff}}$ $Z_b = A_a \left(h - z_a - \frac{1}{2} \frac{n_{pl} \; A_a}{b_{eff}} \right)$
	Dans l'aile supérieure: $A_a - 2 \, b \, t_f \leq \frac{A_c}{n_{pl}} < A_a$	$z_b = h_a + \frac{1}{2b} \left(\frac{A_c}{n_{pl}} - A_a \right)$ $Z_b = \frac{A_c}{n_{pl}} z_c - A_a \; z_a + b \left(h_a^2 - z_b^2 \right)$
	Dans l'âme: ① $A_a - 2 \, b \, t_f > \frac{A_c}{n_{pl}}$	$z_b = \frac{1}{2 \, t_w} \left(\frac{A_c}{n_{pl}} - A_a \right) + \frac{b \, t_f}{d} + h_a - t_f$ ① $Z_b = \frac{A_c}{n_{pl}} z_c - A_a \, z_a + 2 \, b \, t_f \left(h_a - \frac{t}{2} \right) + t_w \left(h_a - t_f \right)^2 - t_w \; z_b^2$

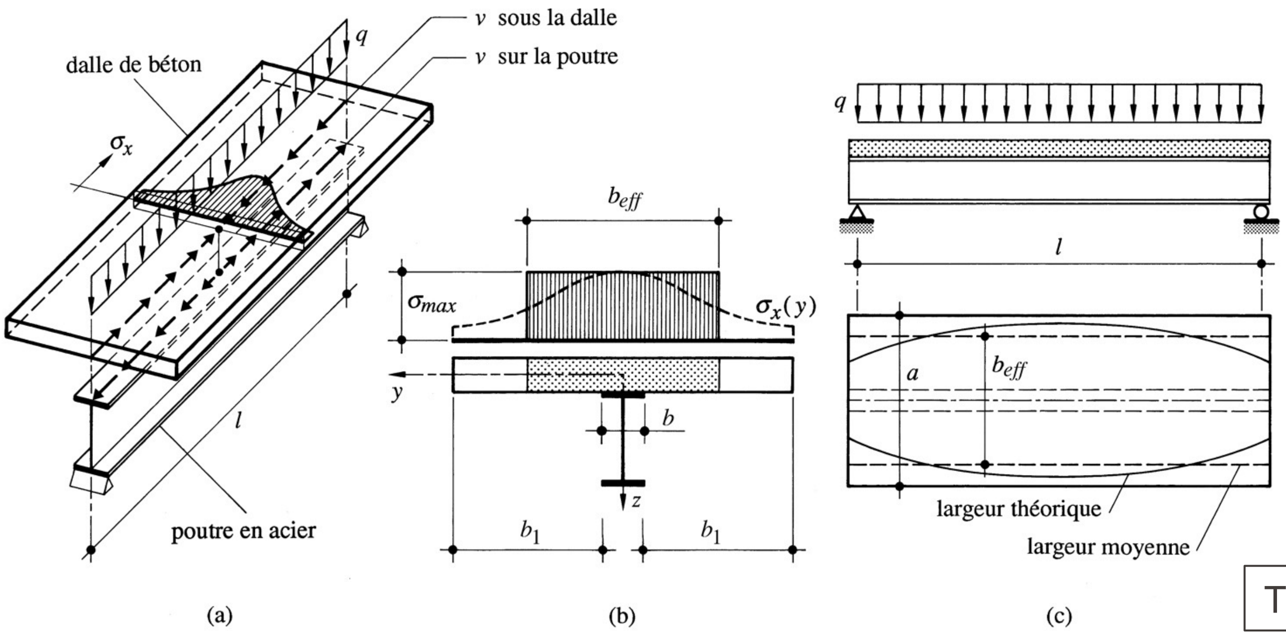
TGC 11, tab. 10.23: PLASTIC char. of a composite section (continued)

$Z_b = W_{pl,b}$

Sur appui	Dans l'aile supérieure : $A_a - 2\,b\,t_f \leq \dfrac{A_s}{n\,pls} < A_a$	$z_b = h_a + \dfrac{1}{2\,b}\left(\dfrac{A_s}{n\,pls} - A_a\right)$ $Z_b = \dfrac{A_s}{n\,pls}\,z_s - A_a\,z_a + b\left(h_a^2 - z_b^2\right)$
	Dans l'âme : ① $A_a - 2bt_f > \dfrac{A_s}{n\,pls}$	$z_b = \dfrac{1}{2\,t_w}\left(\dfrac{A_s}{n\,pls} - A_a\right) + \dfrac{b\,t_f}{t_w} + h_a - t_f$ ① $Z_b = \dfrac{A_s}{n\,pls}\,z_s - A_a\,z_a + 2\,b\,t_f\left(h_a - \dfrac{t_f}{2}\right) + t_w\left(h_a - t_f\right)^2 - t_w\,z_b^2$

① Dans le cas d'un profilé laminé en double té, prendre $A_a = 2\,b\,t_f + (h_a - 2\,t_f)\,t_w$

Shear lag ⇔ participating width

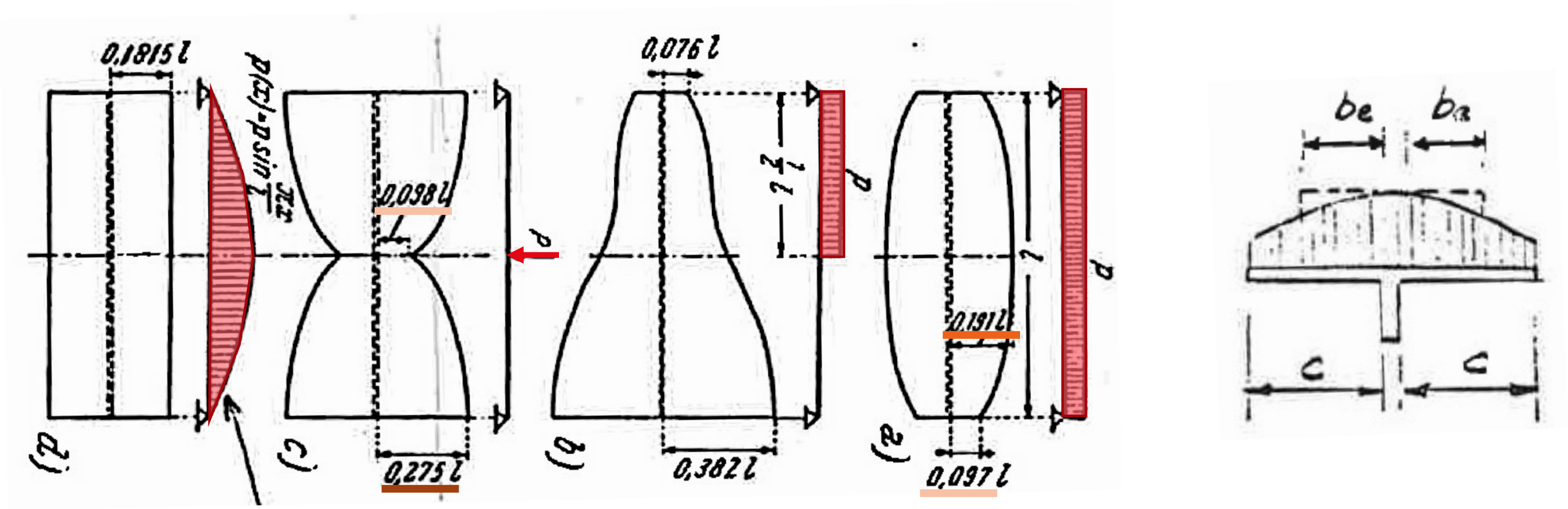


TGC 10, fig. 5.36

function of:

- Static system
- Span
- Type of load

Theoretical values for the participating width of the slab of a T-beam (under ≠ loads)



Ref: Girkmann, K., Flächentragwerke, Springer, Vienna, 1956, p. 125 (and later editions)

Application rules participating width of a concrete slab

ATTENTION, change of notation

$$b_{eff} = \sum b_{eff,i} + b_w \leq b$$

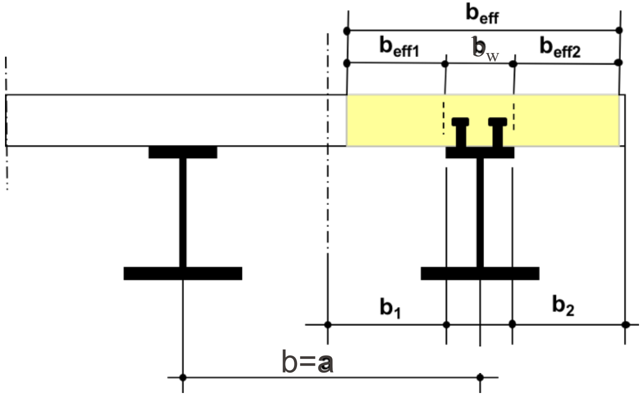
SIA 262 § 4.1.3.3

SIA 264 § 4.3.1.2

(or EN 1994-1-1)

with

$$\begin{cases} b_{eff,i} = 0{,}2 \cdot b_i + 0{,}1 \cdot L_0 \leq 0{,}2 \cdot L_0 \\ L_0 \quad \text{distance between points of zero moments ("equivalent span")} \end{cases}$$



EN1994	SIA 262 SIA 264 (nouv.)	SIA 264 (ancien) et TGC10
b	b	a
b_0	b_w	b
L_e	L_0	L_0

Application rules part width concrete slab

EN 1994-1-1 § 5.4.1.2

- At mid-span or at an intermediate support:

$$b_{eff} = b_0 + \sum b_{e,i} \leq b$$

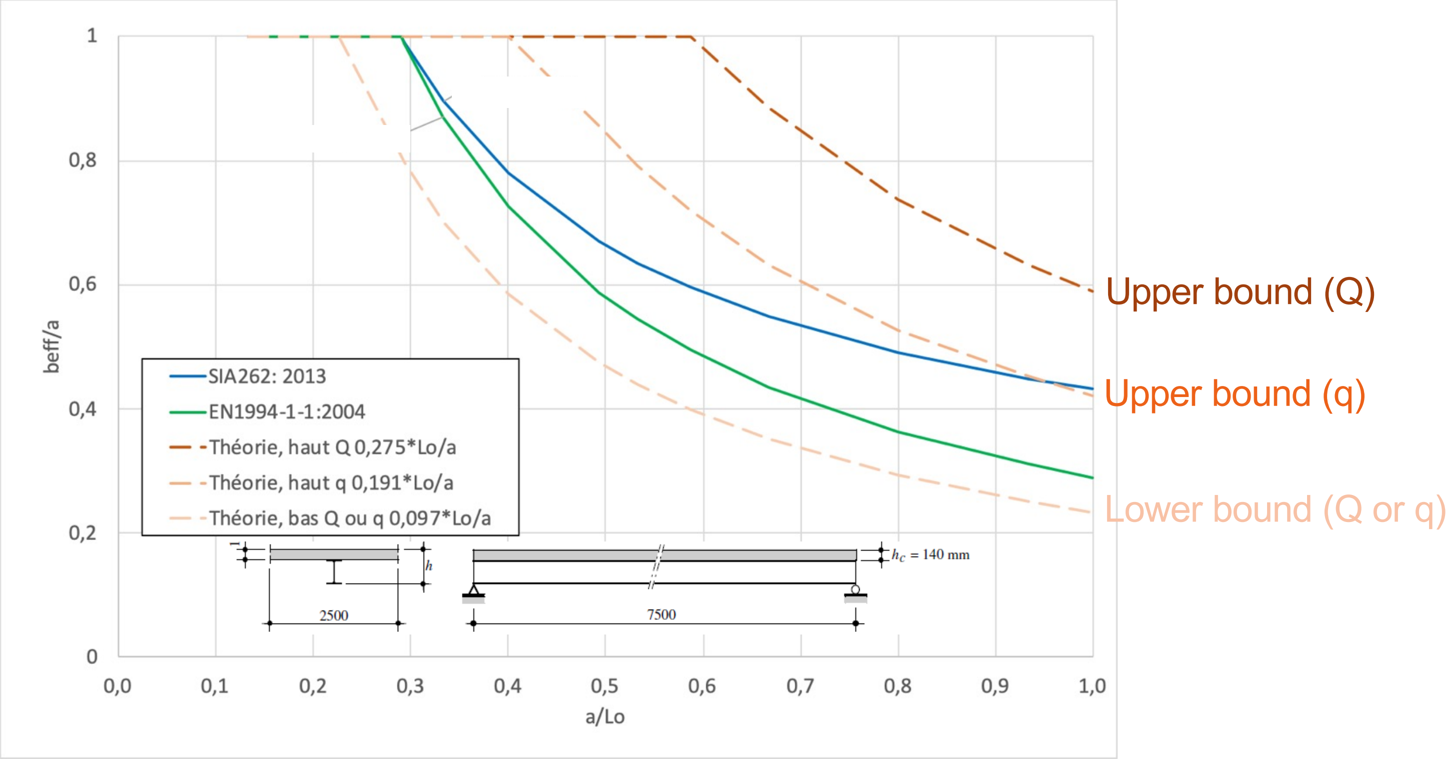
with
$$\begin{cases} b_{e,i} = L_e/8 \leq b_i \\ L_e \quad \text{distance between points of zero moments ("equivalent span")} \end{cases}$$

- At an end support:

$$b_{eff} = b_0 + \sum \beta_i \, b_{e,i}$$

$$\beta_i = (0{,}55 + 0{,}025\, L_e / b_{ei}) \leq 1{,}0$$

Comparison of formulas for determining the participating width



Effective width/spacing (b_{eff}/b)

Spacing/span (b/L)

Application rules for effective width of concrete slab

Global elastic **analysis**, calculation of internal forces:

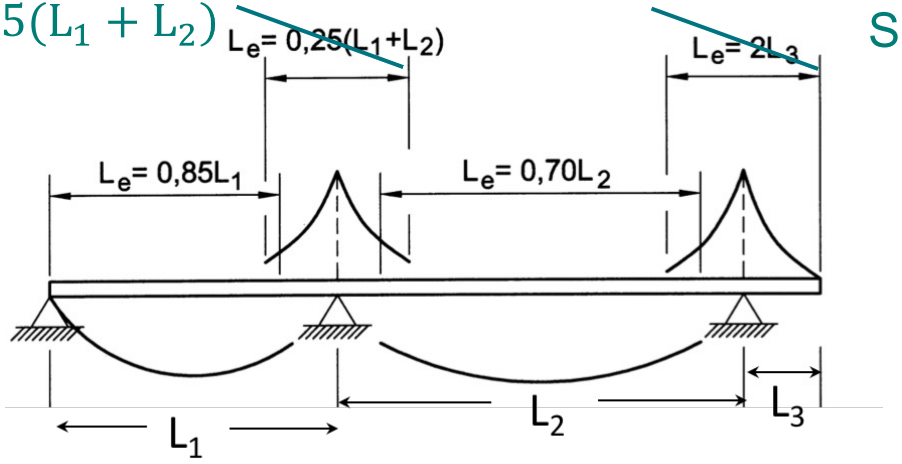
b_{eff}= at mid-span = cste

Verification in section, depending on position. Equivalent span (between zero moment points) :

- Isostatic beam : $l_0 = L_e = L_1$
- Stat. undetermined beam (Eurocode 4 for ex.):

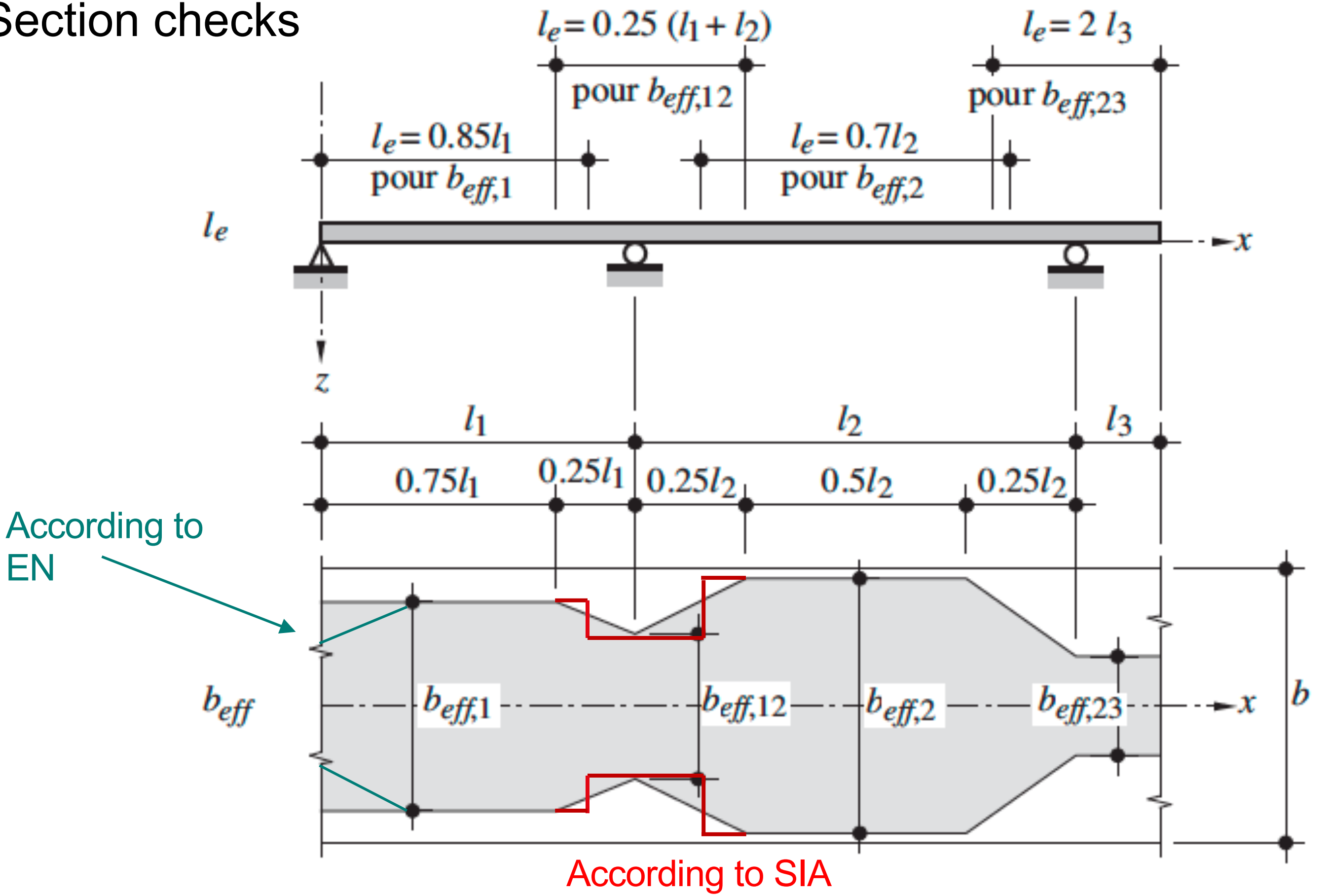
SIA: $L_0 = 0.15(L_1 + L_2)$

SIA: $L_0 = 0.15L_2 + L_3$



Example of participating deck widths (TGC 12)

Section checks

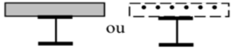
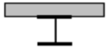
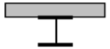
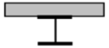
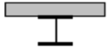


Appendices

REMINDER

Calculation: situations, coeff. and sections to be considered

6) Which statements are correct?

Action	Calcul élastique			Calcul plastique		
	A considérer ?	Section résistante	Coeff. d'équivalence	A considérer ?	Section résistante	Coeff. d'équivalence
Poide propre (profilé, béton)	A) No	B) steel section only	-	OUI	 ou Système statique final	n_{plc} ou n_{pls}
Réaction étais	OUI	 Système statique final		F) No*and**	-	-
Charges permanentes (finitions, isolation, chape, …)						C)
D) Live loads, short duration	OUI	 Système statique final	$n_{el,0}$			
Charges utiles (longue durée)			E)	OUI	 ou … Système statique final	n_{plc} ou n_{pls}
Retrait	OUI***					
Température (ΔT)	OUI	 Système statique final	$n_{el,0}$	NON**	-	-

https://web.speakup.info/room/join/63897

* F) No because connection not active yet

** Self-equil. stresses: cancels out with cracking of the concrete and/or formation of plastic hinges

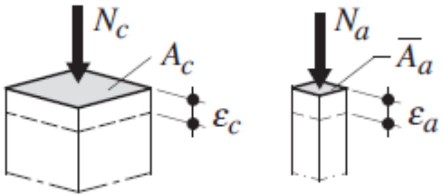
*** Shrinkage: generally neglected for beams in buildings

Reminder: derivation equivalence coefficients

Steel concrete composite elements are calculated by replacing the concrete section with an equivalent steel section using the **equivalence coefficient *n***

Elastic calculation

Béton   Acier équivalent



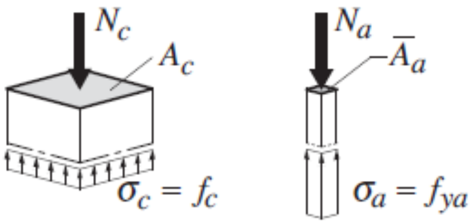
$$N_a = N_c \ et \ \varepsilon_a = \varepsilon_c$$

$$N_a = \sigma_c A_c$$
$$N_a = \sigma_a \bar{A}_a$$

Conditions

Plastic calculation

Béton   Acier équivalent



$$N_a = N_c$$

N_c : effort normal agissant sur la section de béton
N_a : effort normal agissant sur la section équivalente d'acier
σ_c : contrainte agissant sur la section de béton
σ_a : contrainte agissant sur la section équivalente d'acier
A_c : aire de la section de béton
$\bar{A}_a$: aire de la section équivalente en acier

Reminder: derivation equivalence coefficients

Equivalence coefficient *n*

Elastic calculation

$$\overline{A_a} = \frac{A_c}{E_a/E_c}$$

$$n_{el} = \frac{E_a}{E_c}$$

Plastic calculation

$$0.85\frac{f_{ck}}{\gamma_c}A_c = \frac{f_y}{\gamma_a}\overline{A_a}$$

$$n_{pl} = \frac{f_y\gamma_c}{0.85\, f_{ck}\gamma_a}$$

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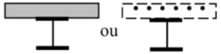
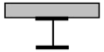
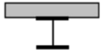
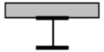
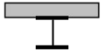
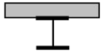
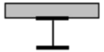
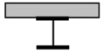
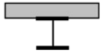
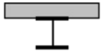
$$\bar{A}_a = \frac{A_c}{n}$$

f_{ck} : valeur caractéristique de la résistance à la compression sur cylindre du béton
f_y : limite d'élasticité de l'acier
γ_a : facteur de résistance pour l'acier (= 1.05)
γ_c : facteur de résistance pour le béton (= 1.5)

SIA 264 § 4.1.5

Plastic calculation conditions:
$\varepsilon >> \varepsilon_{ya}$ (profile)
$\varepsilon >> \varepsilon_{ys}$ (armatures)
$\varepsilon \leq \varepsilon_{cu}$ = 0.3 % (concrete)
Standard beams ok, otherwise reduction SIA 264 § 5.1.2.2

Calculation: situations, coefficients and sections to be considered

Action	Calcul élastique			Calcul plastique		
	A considérer ?	Section résistante	Coeff. d'équivalence	A considérer ?	Section résistante	Coeff. d'équivalence
Poide propre (profilé, béton)	OUI	 Système statique montage	-	OUI	 Système statique final	n_{plc} ou n_{pls}
Réaction étais	OUI	 Système statique final	$n_{el,\infty}$	NON*et **	-	-
Charges permanentes (finitions, isolation, chape, …)	OUI	 Système statique final	$n_{el,\infty}$	OUI	 ou … Système statique final	n_{plc} ou n_{pls}
Charges utiles (courte durée)	OUI	 Système statique final	$n_{el,0}$	OUI	 ou … Système statique final	n_{plc} ou n_{pls}
Charges utiles (longue durée)	OUI	 Système statique final	$n_{el,\infty}$	OUI	 ou … Système statique final	n_{plc} ou n_{pls}
Retrait	OUI***	 Système statique final	$n_{el,s}$	NON**	-	-
Température (ΔT)	OUI	 Système statique final	$n_{el,0}$	NON**	-	-

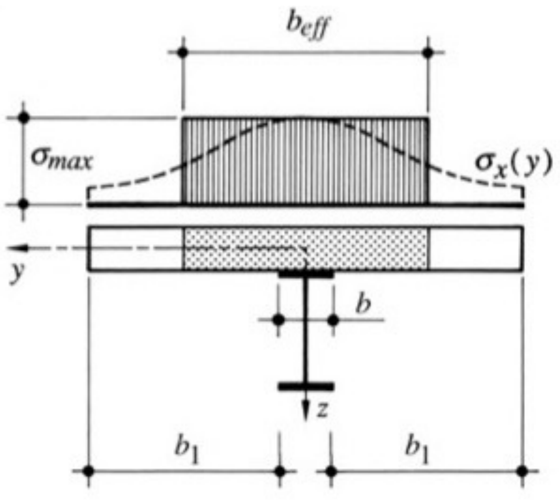
Notes :

* L'effet du fluage se traduit par une diminution de E_C, donc une augmentation de n_{el} => diminution de EI_b. (n'influence que les flèches). En calcul plastique on n'en tient pas compte.

** Les auto-contraintes s'annulent lorsqu'il y a fissuration et/ou formation de rotules plastiques.

*** Cependant négligé d'ordinaire pour les poutres de bâtiment.

TGC 10, fig. 5.36b: Definition of concrete participation width



- Non-uniform real transverse distribution of longitudinal normal stresses
- Important value for dimensioning :
- Equality of the forces transmitted by the fictitious slab and the real slab:

$$b_{eff}.\sigma_{max} = \int_{-b_1-\frac{b}{2}}^{b_1+\frac{b}{2}} \sigma_x(y)dy$$