EPFL

Steel-concrete composite beams Part b

(ref. TGC 10 chap.4 -5 and TGC 11 § 10.5)

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RESSLab

CIVIL526-Steel structures, selected chapters

Overall content

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

Contents part b

- Structural analysis
- Structural verification, ULS
  - Construction stage and loads
- Serviceability check, SLS
- Special loads to consider
- Appendices

Structural analysis

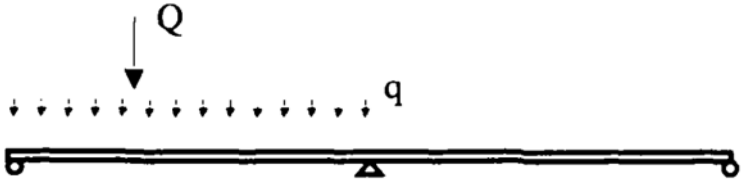
TGC 10 § 4.7.4

TGC 11 §10.5.3

Principle for determining internal forces, and calculation method

Position 1, max moment in span

Position 1, moment max en travée



Position 2, max moment at support

Position 2, moment max sur appui

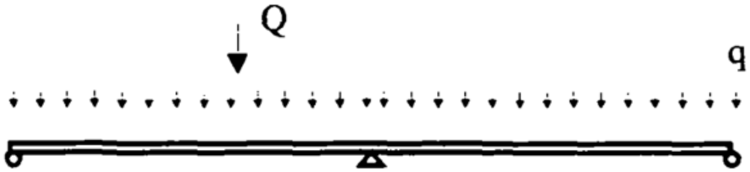
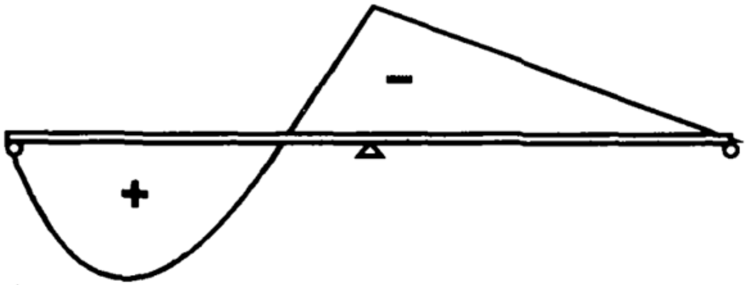


Diagramme des moments

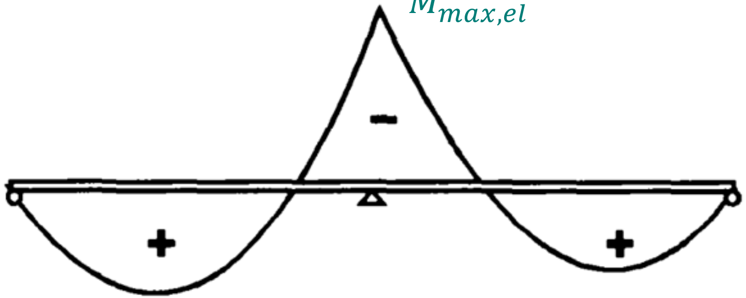
Moment diagram



a)

$M^{+}_{max,el}$

$M^{-}_{max,el}$

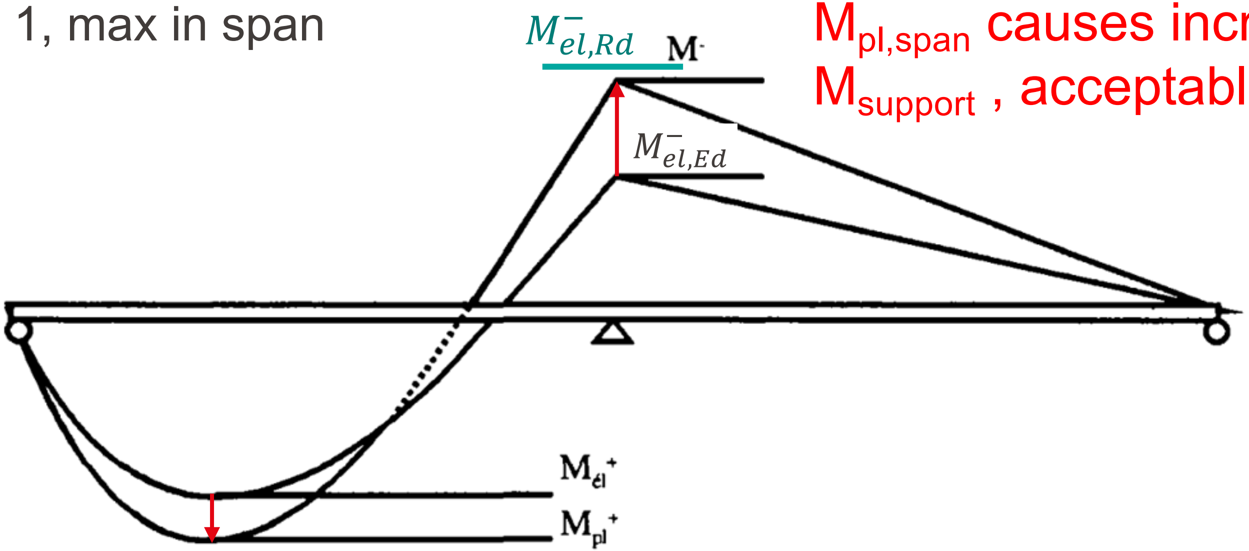


b)

Principle for determining internal forces, and calculation method

Position 1, max in span

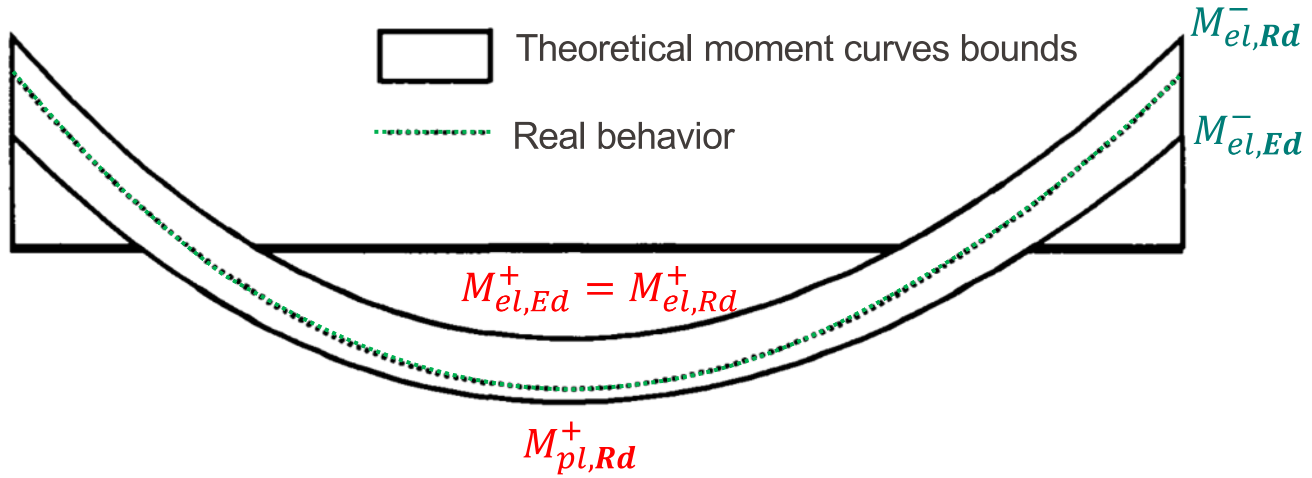
$M_{pl,span}$ causes increase in $M_{support}$, acceptable?



Yielding in span

Principle for determining internal forces, and calculation method

Position 1, max in span

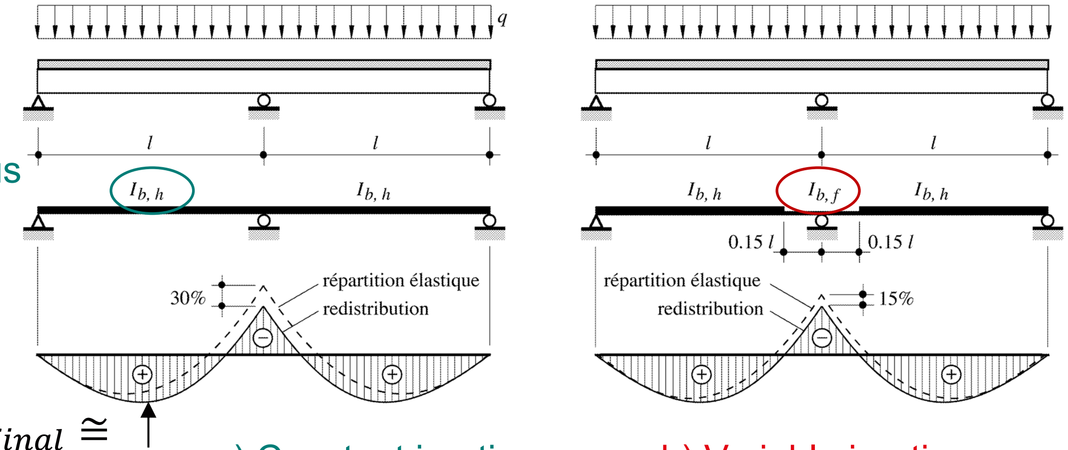


Determining internal forces, M_{Ed} : Elastic calculation, what inertia(ies)?

1st approximation take $I_{b,h}$ = cste (span, b_{eff} =cste) and L_{span} = cste

Influence of variable stiffness, simplified method (TGC 11, fig.10.25, Tab. 10.26)

Homogeneous cross-section (span) inertia



Inertia of cracked cross-section (support)

$M_{tr,final} \cong M_{tr} + 30\% M_{ap}$

a) Constant inertia

b) Variable inertia

Section class in zones M-

	Calcul élastique des efforts intérieurs avec :	Section de classe 1	Section de classe 2
a)	• inertie constante (section non fissurée), fig. 10.25(a)	40%	30%
b)	• inertie variable (section fissurée sur appui), fig. 10.25(b)	25%	15%

Max. % redistribution SIA 264 § 4.2.3.4

SIA 264, redistribution des moments obtenus par calcul élastique (english next)

4.2.3.4 La redistribution des moments fléchissants obtenus par une analyse élastique peut être modifiée, tout en respectant l'équilibre, pour tenir compte des effets de la fissuration du béton, du comportement non élastique des matériaux et du voilement local des éléments structuraux en acier.

Pour des poutres mixtes continues, de hauteur constante, il est possible de modifier les moments fléchissants résultant d'une analyse élastique en réduisant les moments fléchissants maximaux sur appuis selon les pourcentages indiqués dans le tableau 4 et en augmentant en conséquence les moments en travée correspondants.

Tableau 4: Réduction maximale des moments fléchissants résultant d'une analyse élastique

Classe de section dans les zones de moments fléchissants négatifs	1	2	3	4
Calcul élastique sans prise en compte de la fissuration	40%	30%	20%	10%
Calcul élastique avec prise en compte de la fissuration	25%	15%	10%	0%

4.2.3.5 La résistance ultime plastique des sections en travée des poutres continues et des traverses de cadres tenus latéralement qui remplissent les conditions de la classe de section 2 peut être utilisée lors de la vérification, même si les sections ne remplissent pas ces mêmes conditions dans la zone des appuis et pour autant que la résistance élastique de la section dans la zone des appuis ne soit utilisée qu'à 90% au plus, pour le cas de charge considéré. La vérification au déversement dans la zone des appuis doit alors être effectuée selon la norme SIA 263.

SIA 264, redistribution of moments obtained by elastic calculation

4.2.3.4 The redistribution of bending moments obtained by elastic analysis can be modified, while maintaining equilibrium, to take account of the effects of cracking in concrete, inelastic behaviour of materials and local buckling of structural steel members.
For continuous composite beams of constant height, the bending moments obtained by elastic analysis can be modified by reducing the maximum bending moments at supports by the percentages shown in Table 4 and increasing the corresponding span moments accordingly.

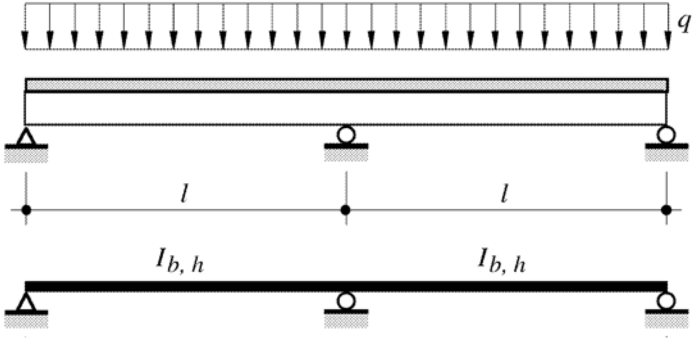
Table 4: Maximum reduction in bending moments resulting from elastic analysis

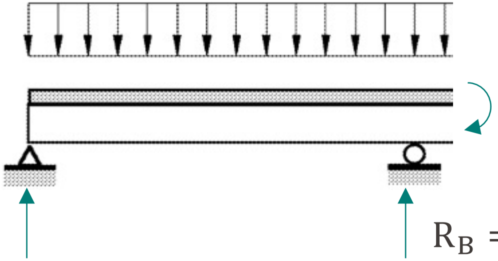
Section class in areas of negative bending moments	1	2	3	4
Elastic calculation without taking cracking into account	40%	30%	20%	10%
Elastic calculation including cracking	25%	15%	10%	0%

4.2.3.5 The ultimate plastic resistance of the cross-sections of continuous beams as well as of laterally held frames that meet the requirements of section class 2 may be used in the verification, even if the cross-sections do not meet these same requirements in the supports area, provided that the elastic resistance of the cross-section in supports area is only used to a maximum of 90% for the load case under study. The torsional buckling check in the supports area must then be carried out in accordance with SIA 263.

Translated with help of DeepL

Determination of internal forces, M_{Ed} : Elastic calculation, redistribution





$M_B = (1 - r)M_{Ed}$

$R_B = q_{Ed} \cdot L - R_A$

Value for e.g. class 2:

r = 30%

$$M(x) = -\frac{q_{Ed}(L-x)^2}{2} - \frac{0.7q_{Ed}L^2}{8} + R_B(L - x)$$

$$x_{max} = \frac{3.3L}{8} = 0.4125L$$

$$M^+_{max} = 0.122\ q_{Ed}L^2$$

In relation to:

Without redistribution, $M^+_{max}(0.37L) = 0.0703\ q_{Ed}L^2$

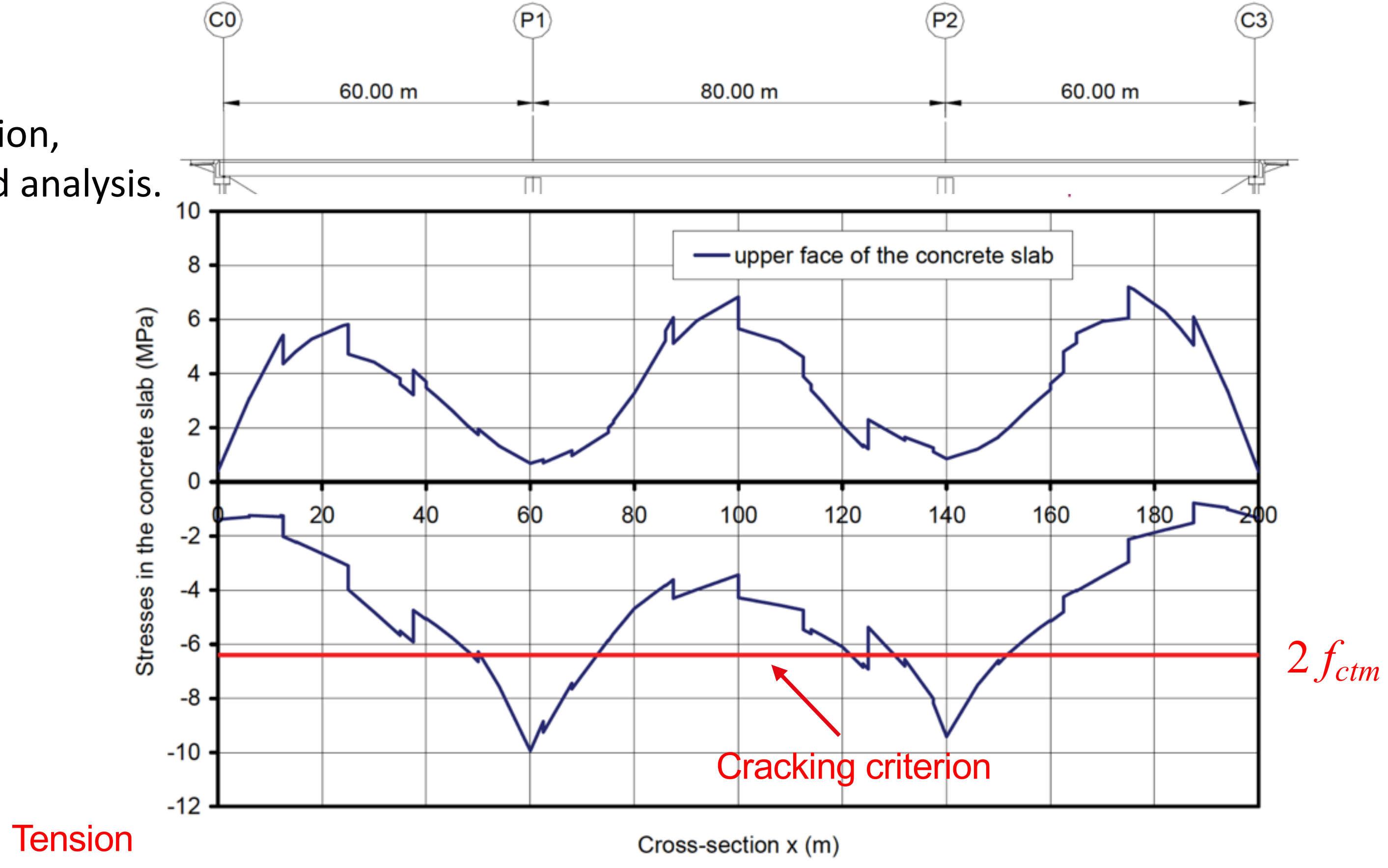
Redistribution, without computing x_{max} (after redist.)

$$M^+_{max} = (0.0703 + 0.3/8)q_{Ed}L^2 = 0.108\ q_{Ed}L^2$$

-

Example (bridges) for calculating cracked zones

1ère iteration,
uncracked analysis.

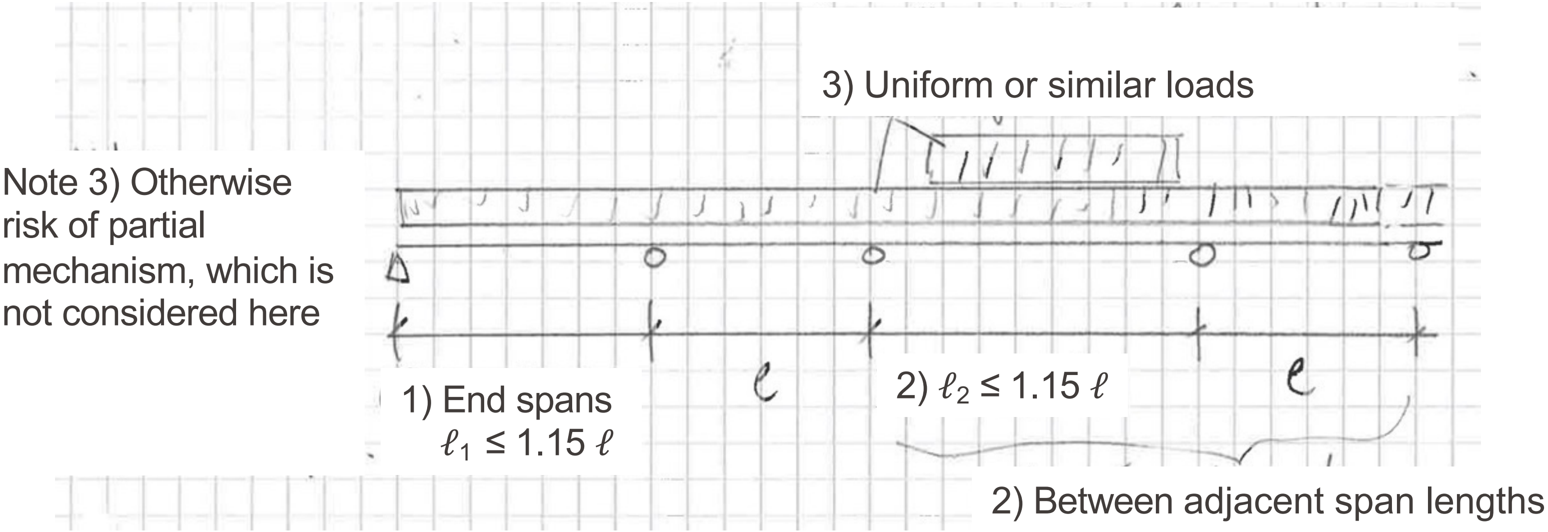


Determination of internal forces, , plastic calculation (PP)

For a plastic-plastic calculation (only for buildings):

- Section class 1, bisymetrical steel cross-section
- Closer to real ultimate state behaviour
- 3 additional requirements:

SIA 264 § 4.2.3.1



Structural safety

TGC 10 § 4.7.4

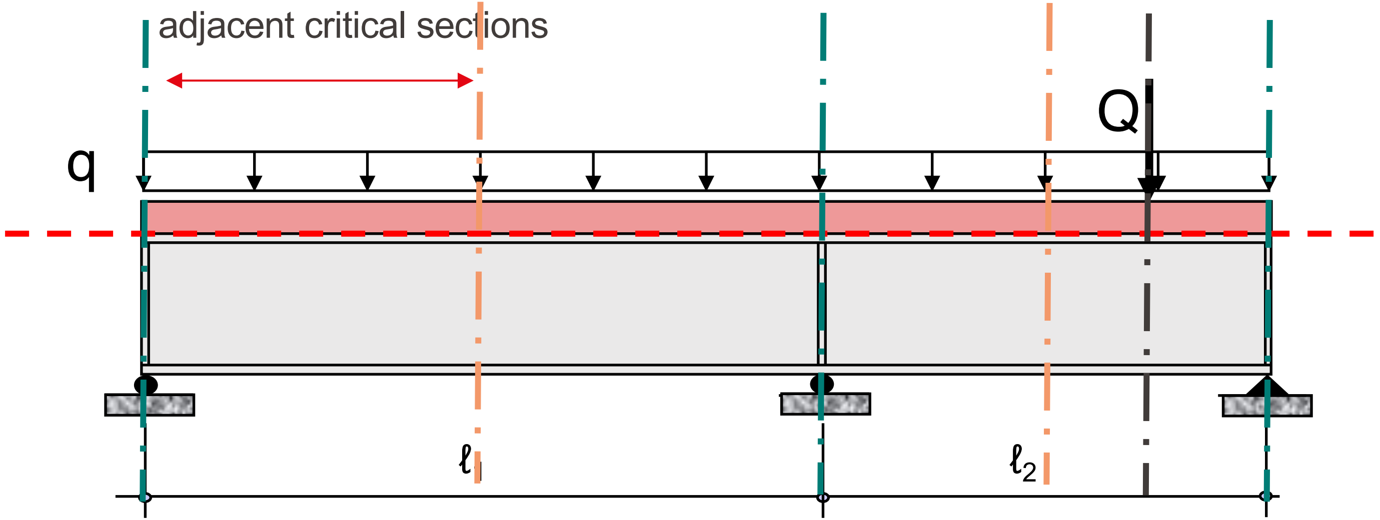
TGC 11 §10.5.3

ULS checks

Critical sections

- On supports (V, or M^{-} +V), including LTB
- In span, M^{+}_{max}
- At loads Q positions
- At major cross-section changes

Shear " length " :
Distance between 2 adjacent critical sections



Connection and longitudinal shear

STOP

TGC 11, "Automatic" LTB check

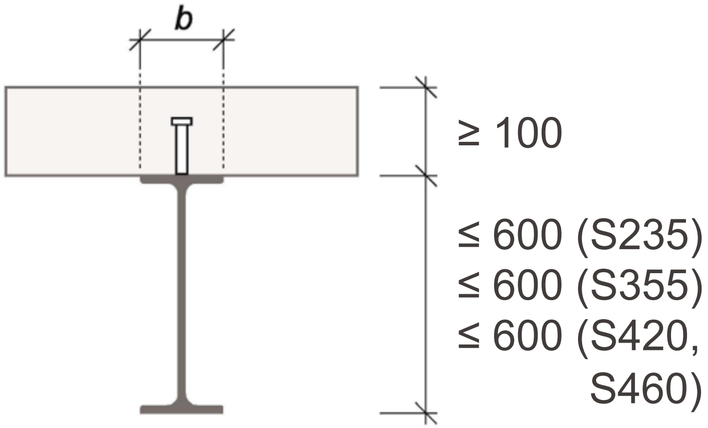
Not necessary to check for LTB at supports of continuous beams if meeting following maximum profile heights (buildings):

SIA 264 §5.1.2.6

- IPE up to 600 mm (S235), or 400 mm (S355), or 270 mm (S420,S460)
- HE up to 800 mm (S235), or 650 mm (S355), or 500 mm (S420,S460)

Prerequisites:

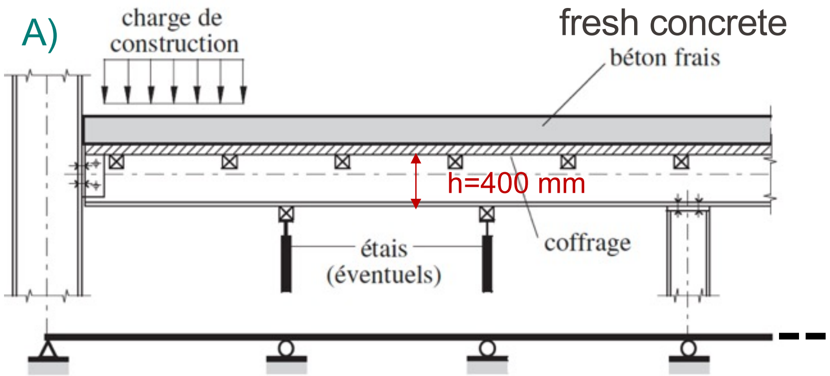
- Vertical stiffeners on supports
- Connection via headed studs
- Slab thickness min. 100 mm (prevents section rotation)



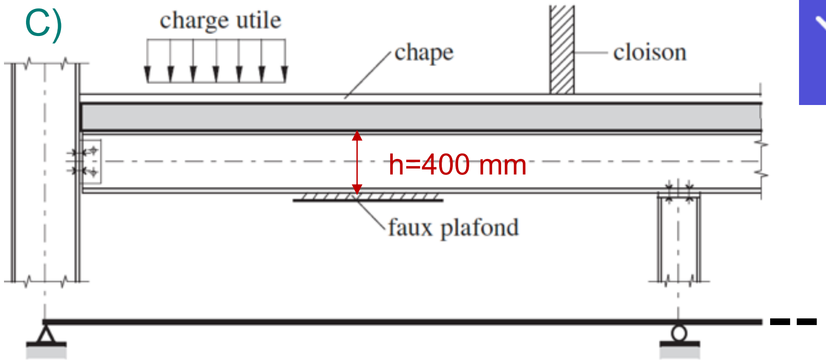
Checking on discharge

7) In which situation should IPE beams LTB be checked (several possibilities)?

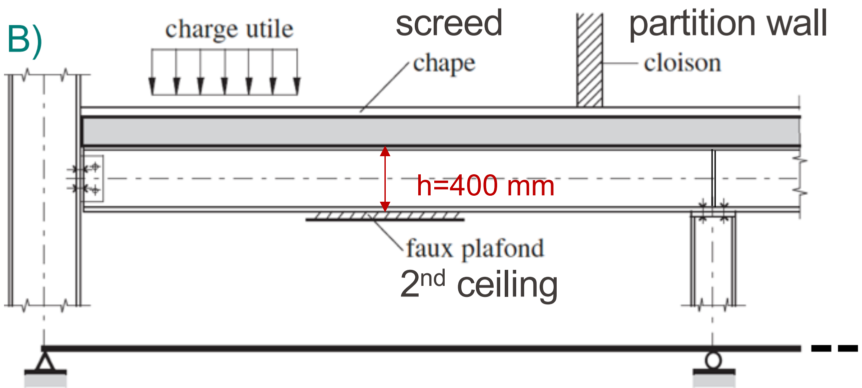
A)



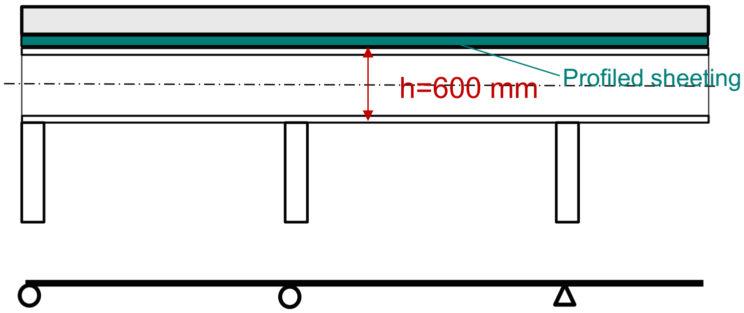
C)



B)



D)



Design/Sizing method, checks

- Whatever the class, elastic checks under M^+ (compressed concrete slab) or under M^- (tensioned and cracked concrete slab):
  - for all fibres in the section (structural steel, concrete, passive reinforcement)

$$\sigma_{Ed,a} = \frac{M_{el}}{I_b} z_b \qquad \sigma_{Ed,c} = \frac{1}{n_{el}} \frac{M_{el}}{I_b} (z_b - h)$$

The load cases are added together

$$\sum_i \sigma_{Ed,i} \leq \frac{f_k}{\gamma_M}$$

- For class 1 or 2 sections, plastic check :

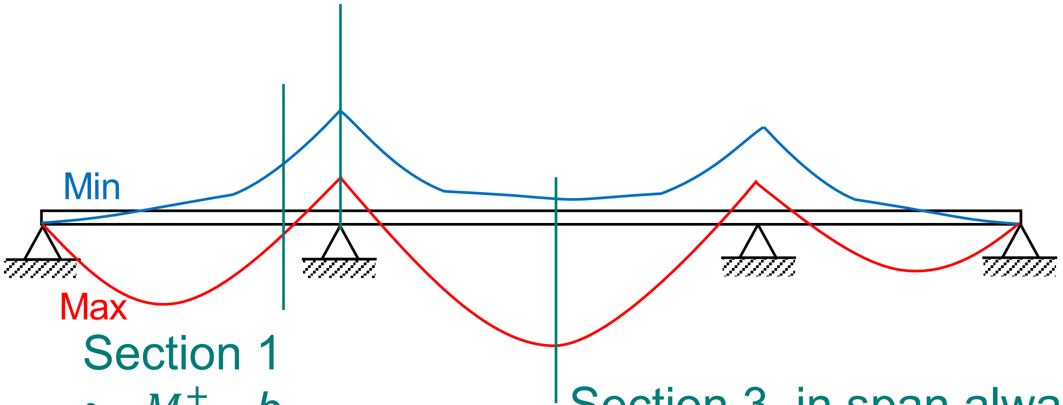
$$M_{Ed} \leq M_{Rd} = M_{pl,Rd}$$

Section checks (EN)

Envelopes of moments & slab effective width

Section 2, on support always

- M_{Ed}^{-}, $b_{\text{eff,ap1-2}}$



Section 1

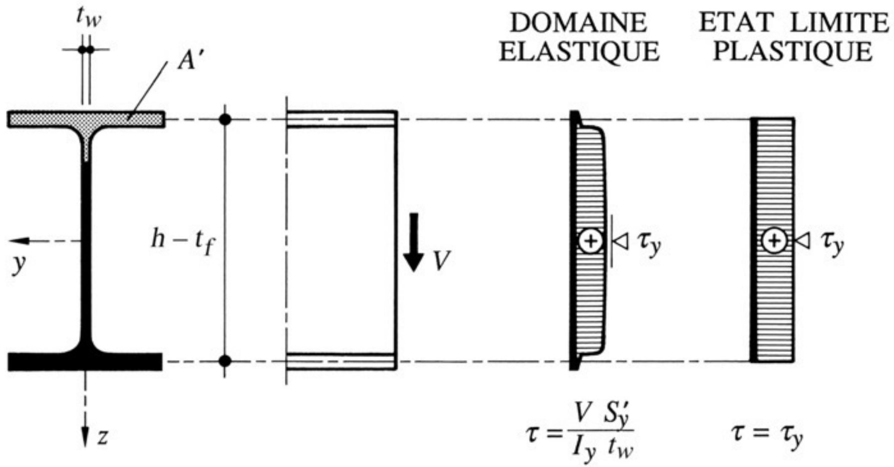
- M_{Ed}^{+}, $b_{\text{eff,tr1}}$
- M_{Ed}^{-}, $b_{\text{eff,ap1-2}}$

Section 3, in span always

- M_{Ed}, $b_{\text{eff,tr2}}$

Shear strength (SIA 264 §4.3.2.2)

- Shear strength → same as steel beam → SIA 263
- Shear force taken by the steel section web
- M+V interaction, also in accordance with SIA 263



$$V_{Rd} = \frac{f_y \cdot A_V}{\sqrt{3} \cdot \gamma_{M1}}$$

Castellated profiles (SZS C5, p.84): approx. with (A_w - opening), or according to producer tables

Construction stage
Loads to be considered

TGC 10 § 5.8.3

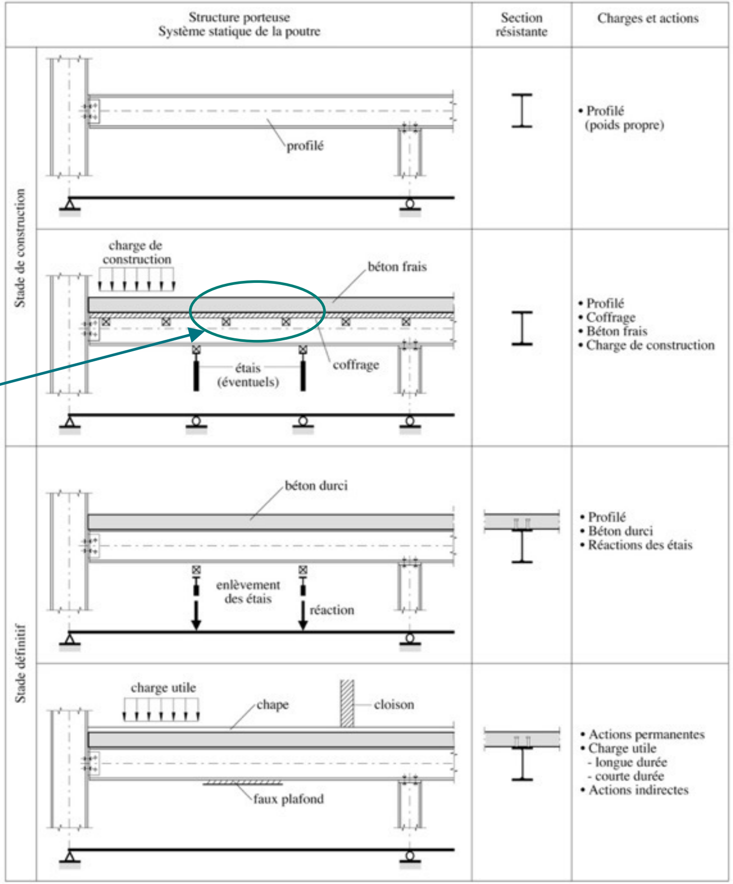
TGC 11 § 10.5.3 and 10.5.4

TGC 11, fig. 10.24: summary of different stages

Construction stage

Compressed upper flange, LTB at construction stage !

Final stage

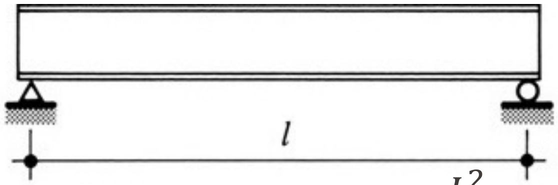


Description of composite structure construction stages

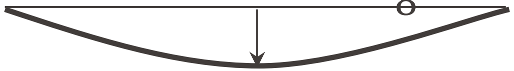
- STEP 1: Erection of the steel beam (using a crane, for example)

  One looks at a beam subjected to sagging (positive bending).

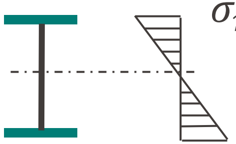
  One considers the most stressed section at mid-span.



$$M_1 = \frac{g_a \cdot L^2}{8}$$



e.n.a steel



$$\sigma_{max} = \frac{M_1}{I_a}\frac{h_a}{2}$$

Load to be carried :

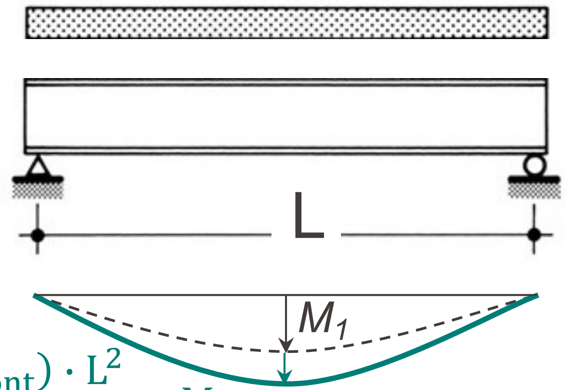
- steel profile self-weight g_a (N/m)

Resistant section :

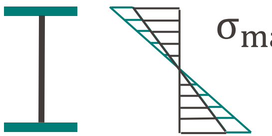
- steel section A_a
- inertia I_a

Description of composite structure construction stages

- STEP 2: Concreting the concrete slab



$$\frac{(g_c + g_{mont}) \cdot L^2}{8} = M_2$$



$$\sigma_{max} = \frac{(M_1 + M_2)}{I_a} \frac{h_a}{2}$$

Load to be carried :

- Self-weight of timber formwork, concrete reinforcement and fresh concrete g_c (N/m)

Resisting section :

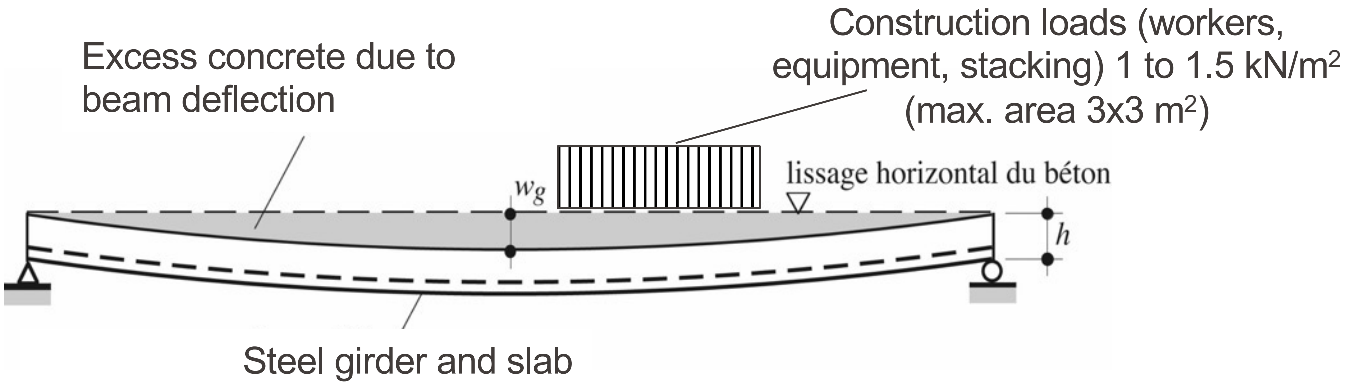
- steel only section A_a
- inertia I_a

Transitional situation where the steel section is subjected to the greatest stress. EE calculation

Watch out for LTB !!!

TGC 11, fig. 6.5: beware of deformation during this stage!

- STEP 2: Concreting of concrete slab



In addition of stress checks:

SIA 264 § 5.4.4.4

- Compute deflection, surplus to be considered if : $w_g \geq h/10$
- Deflection limit (w/o surplus): $w(g_a + g_c + (g_{surplus}) + g_{montage}) \leq L/300$
- Differences of M, w between parabolic and uniform load?

$M(L/2)_{para} = 5g_{surplus}\, L^2/48$ **5/6**

$w_{max,para} = 61 g_{surplus}\, L^4/(5760EI)$ **61/75**

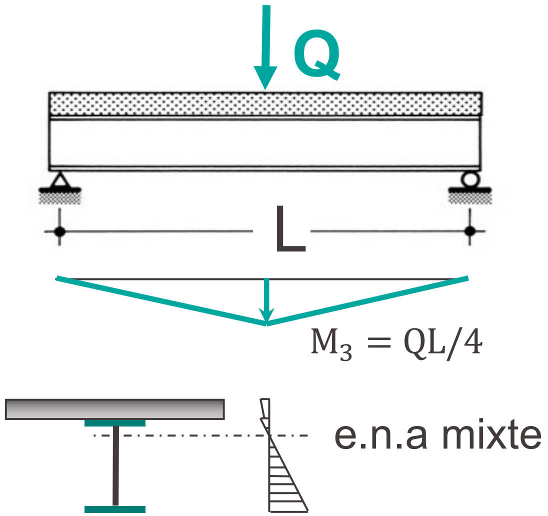
$\leftrightarrow g_{surplus} \approx 0.7 w_g \rho_c$

Description final stage composite structure

- STEP 3: **The concrete hardens and becomes resistant**

  The behaviour of the structure becomes **composite**

- STEP 4: Application of other permanent and live loads



Load to be carried :

- e.g. concentrated load Q (N)

Resisting section: steel + compressed concrete

- section $A_b = A_a + (A_s) + A_c / n_{el}$
- inertia I_b

For the calculation of deflections and for the EE calculation:
Value of the coefficient n_{el} of equivalence to be defined

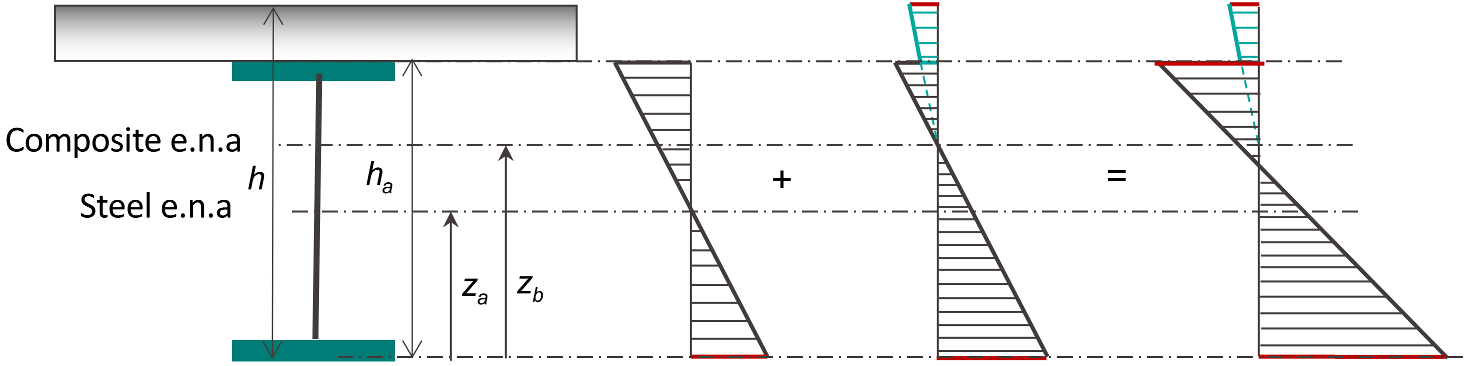
Addition of construction and final stages

- Addition at the **final elastic stage**

$M_{Ed,a}$ = moment taken by the beam in steel-only behaviour

$M_{Ed,b}$ = moment taken by the beam in composite behaviour

$$\sigma_{Ed,c} = \frac{1}{n_{el}} \frac{M_3}{I_b} (z_b - h) \qquad \sum_i \sigma_{Ed,c,i} \leq \frac{f_{ck}}{\gamma_c}$$



$$\sigma_{Ed,a} = \frac{(M_1 + M_2)}{I_a} \frac{h_a}{2} \qquad \sigma_{Ed,a} = \frac{M_3}{I_b} z_b \qquad \sum_i \sigma_{Ed,a,i} \leq \frac{f_y}{\gamma_a}$$

Note: several diagrams depending on the duration of load application (fct of $n_{el,i}$)

Addition of construction and final stages

- Addition at the **final elastic stage**

$M_{Ed,a}$ = moment taken up by the beam in steel-only behaviour

$M_{Ed,b}$ = moment taken up by the beam in composite behaviour

ELU, steel stress:

$$\sigma_{Ed,a} = \frac{M_{Ed,\mathrm{a},1-2}}{I_a} z_a + \sum_i \frac{M_{Ed,b,i}}{I_{b,\mathrm{i}}} z_{b,i}$$

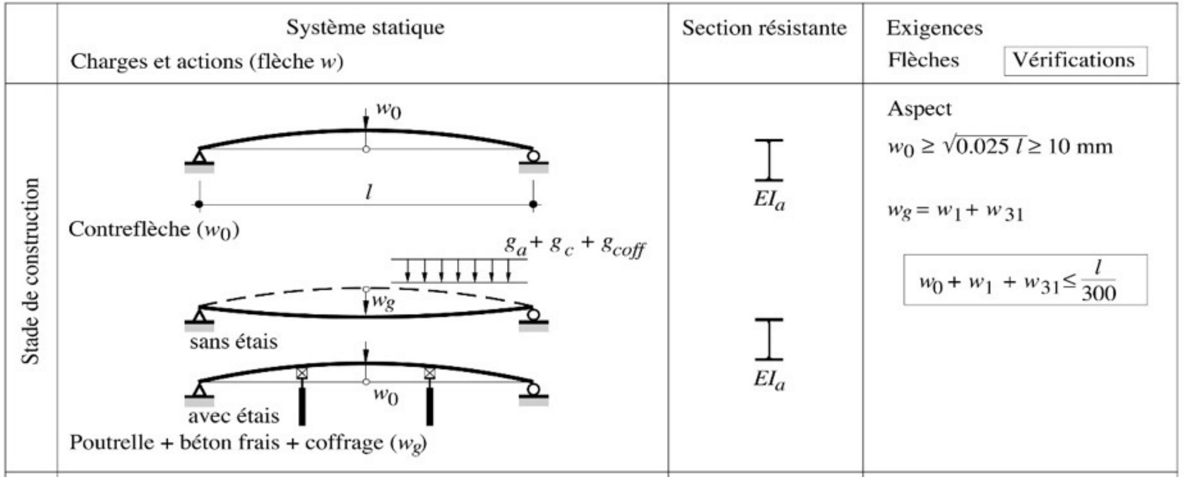
ELU, concrete stress:

$$\sigma_{Ed,c} = \sum_{\mathrm{i}} \frac{1}{n_{el,i}} \frac{M_{Ed,b,i}}{I_{b,\mathrm{i}}} \left(z_{b,i} - h\right)$$

Serviceability

TGC 11 § 10.5.9

TGC 11, fig. 10.46: Checking deflection limits (elastic)

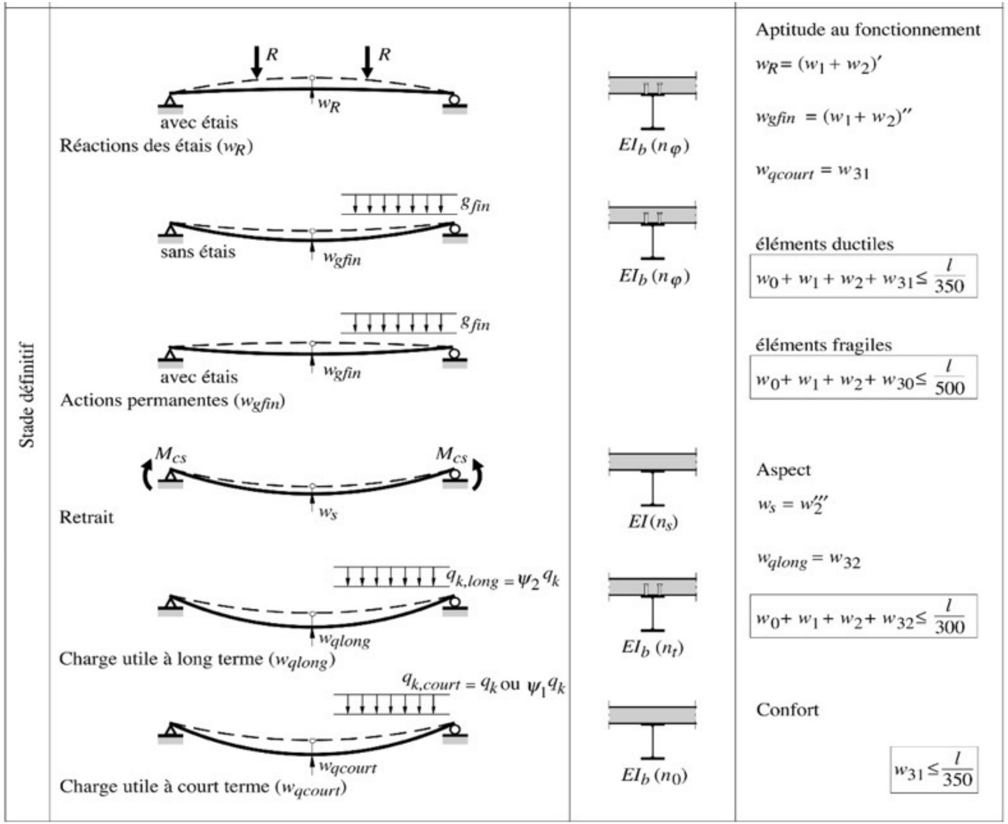


Indices (according to TGC):

0 = precambering
1 = self-weight
2 = other self-weights (and shrinkage defl.)

3 = live loads
- 30 = rare (= short duration)
- 31 = frequent (= short duration)
- 32 = quasi-permanent (= long term)

TGC 11, fig. 10.46: Checking deflection limits (elastic)



$$w_2 = w_2' + w_2'' + w_2'''$$

Addition of construction and final stages

- Addition to the **final elastic stage**

$M_{Ed,a}$ = moment taken by the beam in steel-only behaviour

$M_{Ed,b}$ = moment taken up by the beam in composite behaviour

ELU, steel stress:

$$\sigma_{Ed,a} = \frac{M_{Ed,a,1-2}}{I_a} z_a + \sum_i \frac{M_{Ed,b,i}}{I_{b,i}} z_{b,i}$$

ELS, deflection:

$$w_{tot} = \frac{\alpha_i \cdot q_{Cd,a,1-2}}{E_a\, I_a} + \sum_i \frac{\alpha_i \cdot q_{Cd,b,i}}{E_a\, I_{b,i}}$$

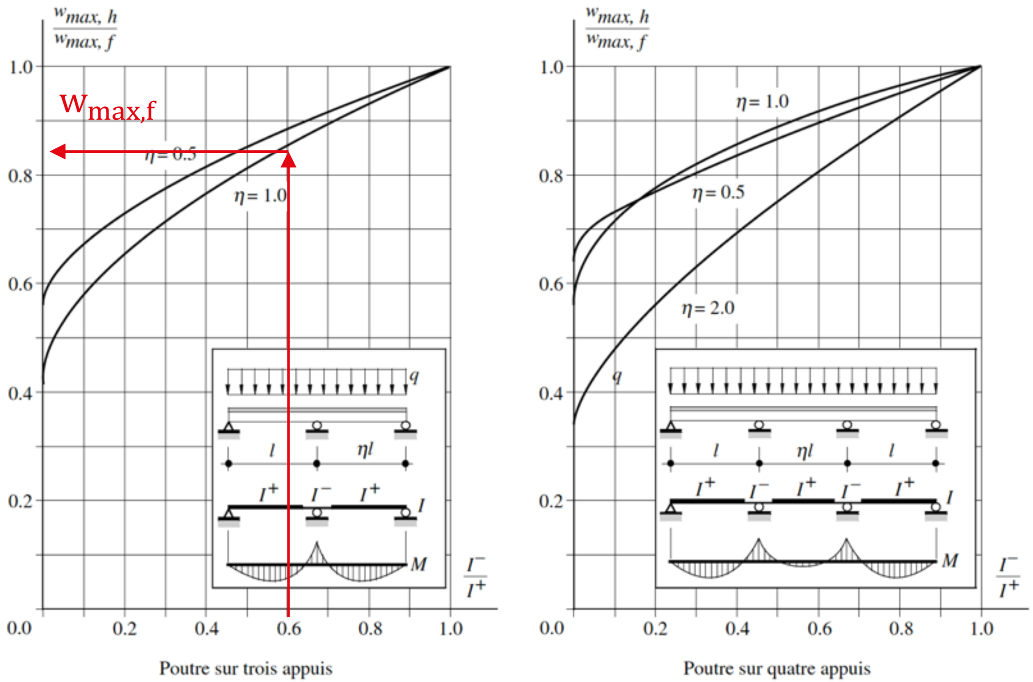
α_i coefficient fct static system & loading ($\frac{L^3}{48}, \frac{L^4}{384}, \frac{5L^4}{384}, \ldots.$)

Checking deflections, influence of concrete cracking (TGC11, fig.10.51)

SIA 264 § 4.6.4, § 5.1.3:

- Internal forces and deflections at ELS
- Elastic calculation method
- Take into account cracking, creep and shrinkage of concrete.

In addition, take into account the flexibility of connection, if significant
(e.g. partial connection).



Special loads to consider
- Prop(s)
- Concrete shrinkage

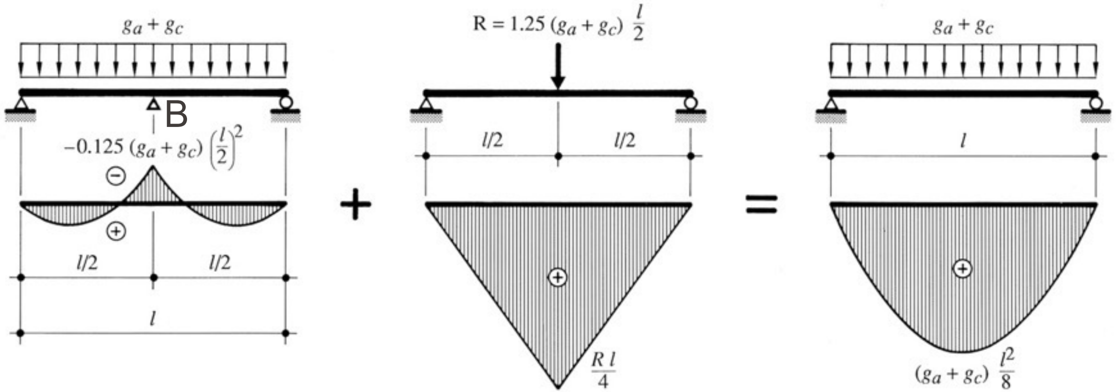
TGC 10 § 5.8.3 and 5.8.5

TGC 11 § 10.5.5

TGC 10, fig. 5.37: mixed structure construction with/without prop

Action-reaction principle

(a) Supported beam (b) Removed prop (c) Final stage



In the end, in both cases:

$$\sum F_i = 0$$

$$\sum F_i \cdot z_i = M_B$$

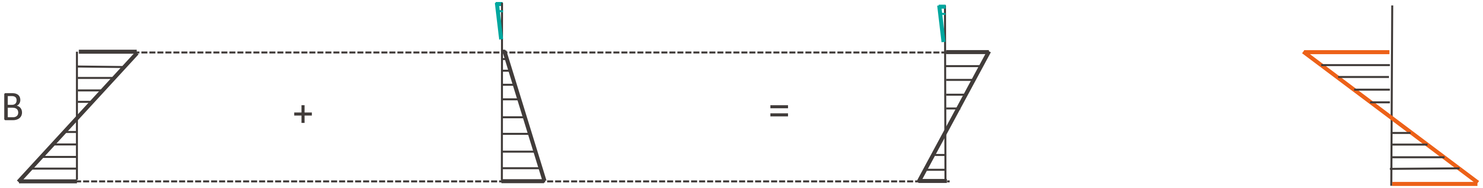
Resisting section = steel only

Resisting section = composite

Resisting section = composite

Without prop

section B



Composite structure construction with/without prop

In the case of a supported beam

- Reduced deflection during concreting
- In the mid-span section, the steel beam is subject to less stress due to the transfer of part of the self-weight of the fresh concrete to the composite beam. For example :

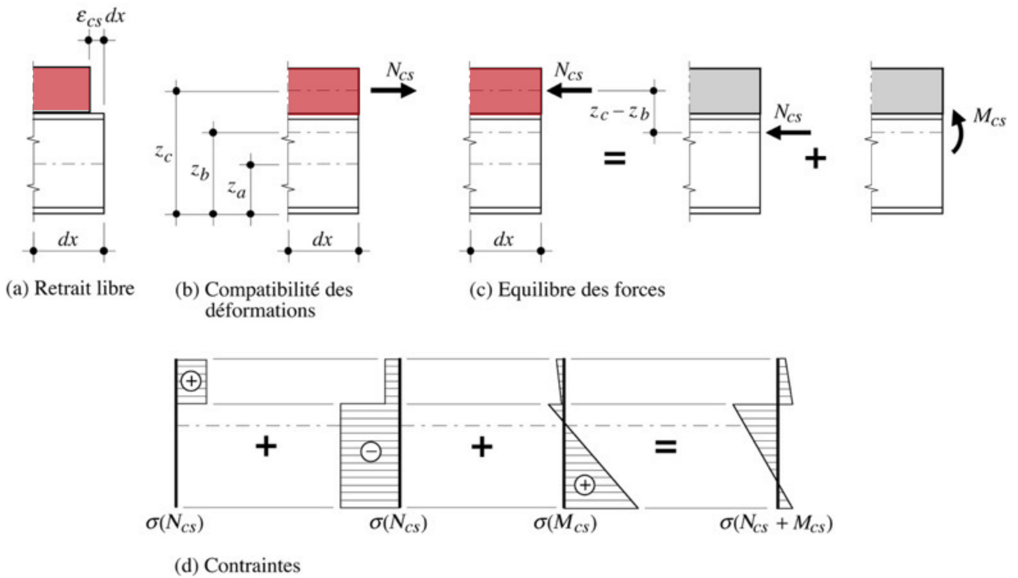
$$M_{a,Ed} = M_1 + M_2 = \frac{0.5(g_a+g_c)L^2}{4}$$ without strut

$$M_{a,Ed} = -\frac{0.125(g_a+g_c)L^2}{4}$$ with prop

Shrinkage phenomenon and internal forces

- Shrinkage = long-lasting action
- SIA 262: $\varepsilon_{cs}(\infty) = 0.5‰$

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



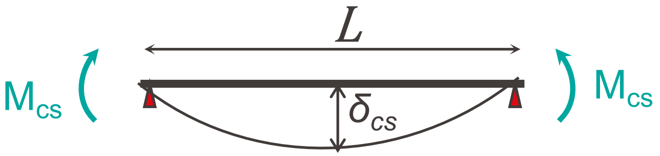
Self-balancing stress state

Determinate systems
M_{Ed} (shrinkage) = 0

But vertical deformations

Calculation of deflections and moments in a composite beam on 3 supports

- The internal moment due to shrinkage M_{cs} creates a deflection (important for verifying serviceability).

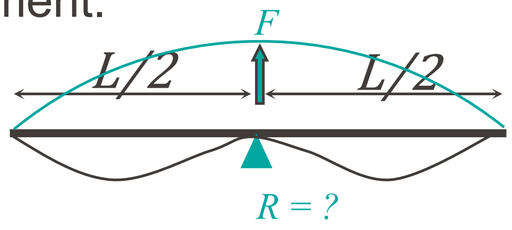


$$\delta_{cs} = \frac{M_{cs} \cdot L^2}{8 E_a I_{mixte}}$$

- Case of a hyperstatic beam, beam on 3 supports :

TGC11 Fig. 10.49

The intermediate support prevents the formation of the deflection expected if the beam were isostatic. Creation of a hyperstatic shrinkage moment.



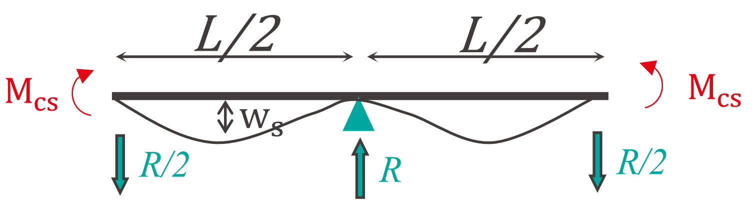
$$\delta_{F,midspan} = -\frac{F \cdot L^3}{48 E_a I_{mixte}} = -\delta_{cs}$$

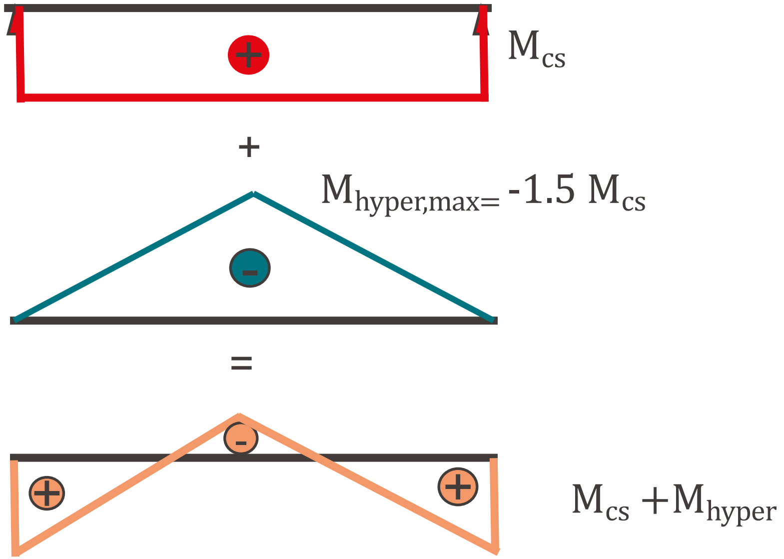
$$R = \frac{6 \cdot M_{cs}}{L}$$

Permanent support (not a prop)

Calculating deflections and moments in a composite beam

- Case of a indeterminate beam, beam on 3 supports :





- Deflections: (TGC11, eq.10.104 to 10.106)

pour une poutre simple: $$w_s = \frac{M_{cs}\ l^2}{8\ E_a\ I_{b,h}}$$

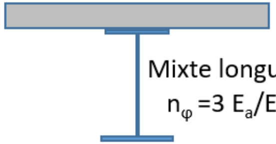
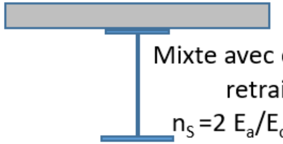
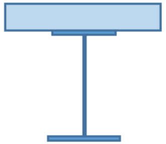
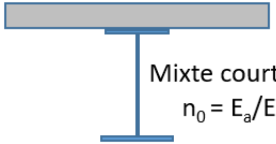
pour une poutre sur trois appuis: $$w_s \cong \frac{M_{cs}\ l^2}{27\ E_a\ I_{b,h}}$$

pour la travée de rive d'une poutre sur quatre appuis et plus:

$$w_s \cong \frac{M_{cs}\ l^2}{20\ E_a\ I_{b,h}}$$

Appendices

Recall: resisting section ⇔ action

Modèle équivalent	Section résistante	Actions
Modèle 0 	 Acier seul	-poids propre de la poutre métallique -poids propre du béton frais -charge de montage
Modèle 1 	 Mixte longue durée $n_{\varphi} = 3\ E_a/E_{cm} = 18$	-Revêtement -Glissière -Fluage
Modèle 2 	 Mixte avec effet du retrait $n_S = 2\ E_a/E_{cm} = 12$	-Effort normal dû au retrait N_{cs} -Moment dû au retrait M_{cs}
Modèle 3 	 Mixte courte durée $n_0 = E_a/E_{cm} = 6$	-Trafic (Q_k et q_k) -Température

Calculation of internal forces ACCORDING TO TGC 12, chap. 13

Inertia can change along the beam (variable steel section, variable b_{eff} , cracking on interm. supports).

Method 1:

- A single analysis: elastic calculation of forces, taking into account the participation of tensile concrete everywhere, with $I_{b,h,cte}$ (building) or $I_{b,h,variable=}$ fct (A_a , b)$_{eff}$
- Flat-rate redistribution r % of intermediate supports to bays (depending on support cross-section class)
- Only for actions taking place after the link has been created.

Method 2a:

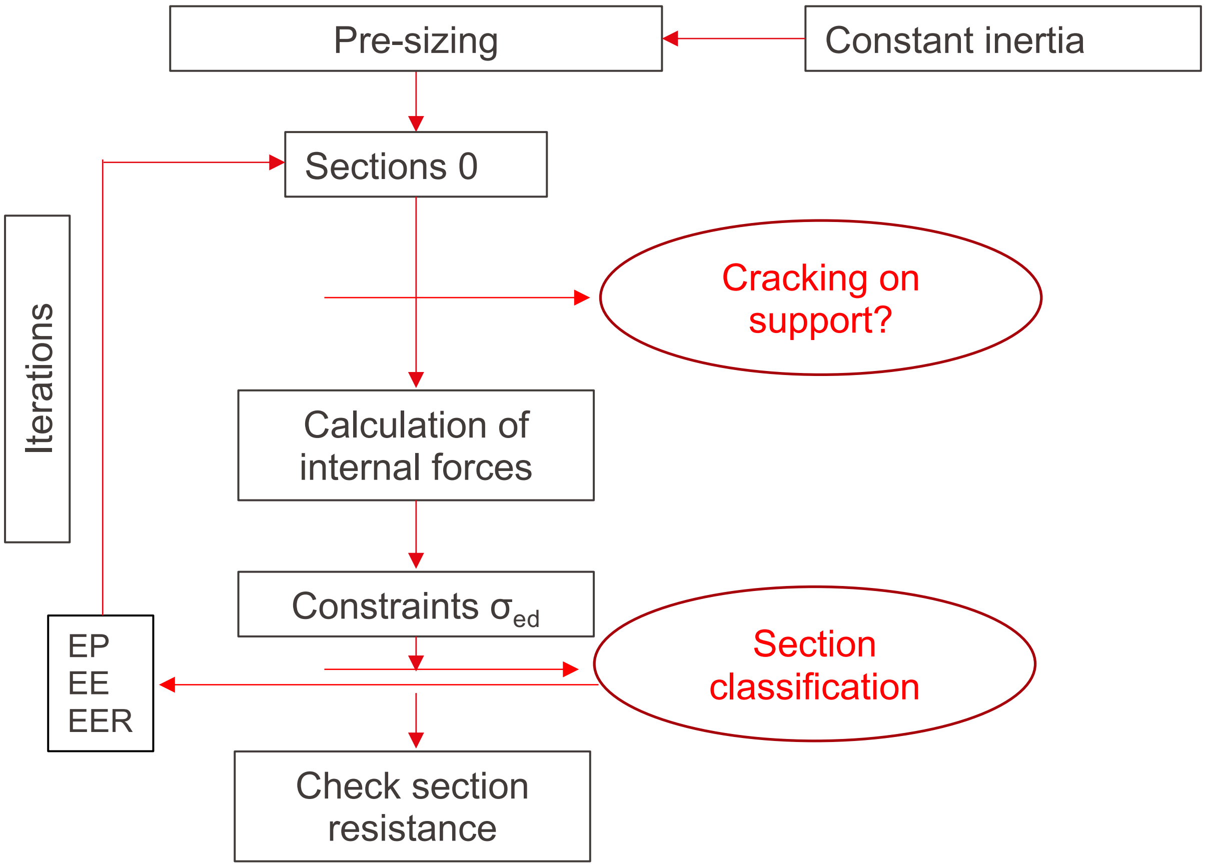
- 1ère analysis: elastic calculation of forces taking into account the participation of concrete stretched everywhere
- Under ELS characteristic load (rare load case), including long-term effects
- In zones M^- , lengths L_{fiss} where , inertia of cracked sections
- 2ème analysis: elastic stress calculation with $I_{variable}$ and cracked sections.

Method 2b:

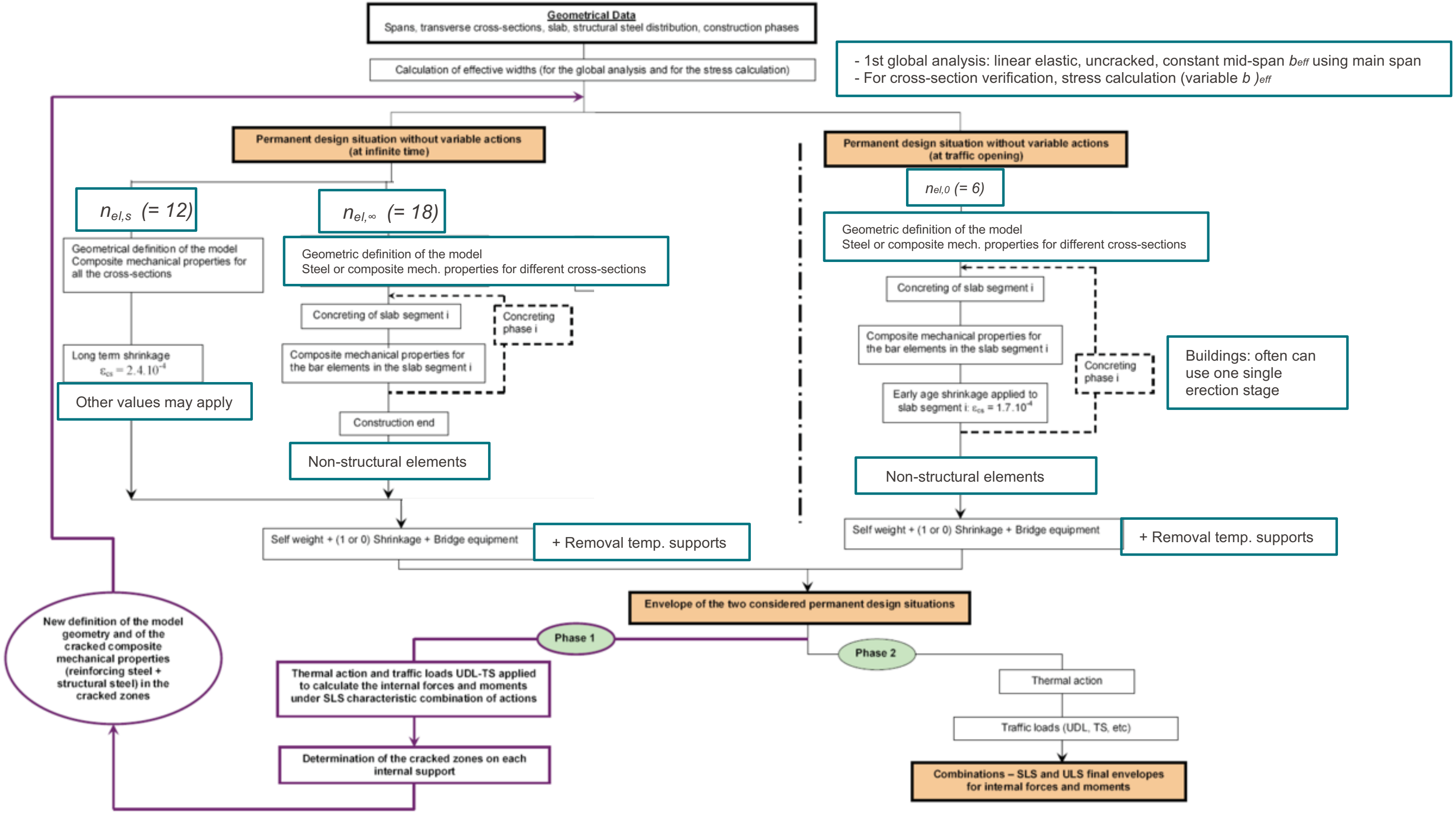
- In-situ concrete slab: analysis with L_{fiss} = 15%, elastic calculation of forces $I_{b,I}$ and $I_{b,II}$ (limit L_{min} /L_{max} > 0.6).

Method 2a: internal stress calculation diagram

1ère analysis



Complete flow chart for mixed bridge calculation, elastic stage



Extract from guidance book bridges SETRA, 2007