Bridge deck modelling and design process for bridges

Application to a composite twin-girder bridge according to Eurocode 4

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INGÉROP

General design process of a bridge

1. **Global analysis**
    a. Calculate the internal forces and moments according to Eurocode’s principles
    b. By modelling the bridge deck (geometry and stiffness to represent its actual behaviour in the best way)
    c. And by applying the load cases
2. **Section and member analysis**
    a. Stress limitations at ULS and SLS
    b. Concrete crack width control
    c. Stability (plate or member buckling)
    d. Connection at the steel–concrete interface
    e. Fatigue

Steel concrete composite bridges

The twin-girder composite bridge represents a large majority of the new road and railway bridges built in France:

- Usual span length: 40 m < L < 80 m
- Deck width up to 22 m (2 x 2 highway lanes) with connected cross-girders

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- Competitive solution
- Simple design
- Quick construction process
- Reliable structure

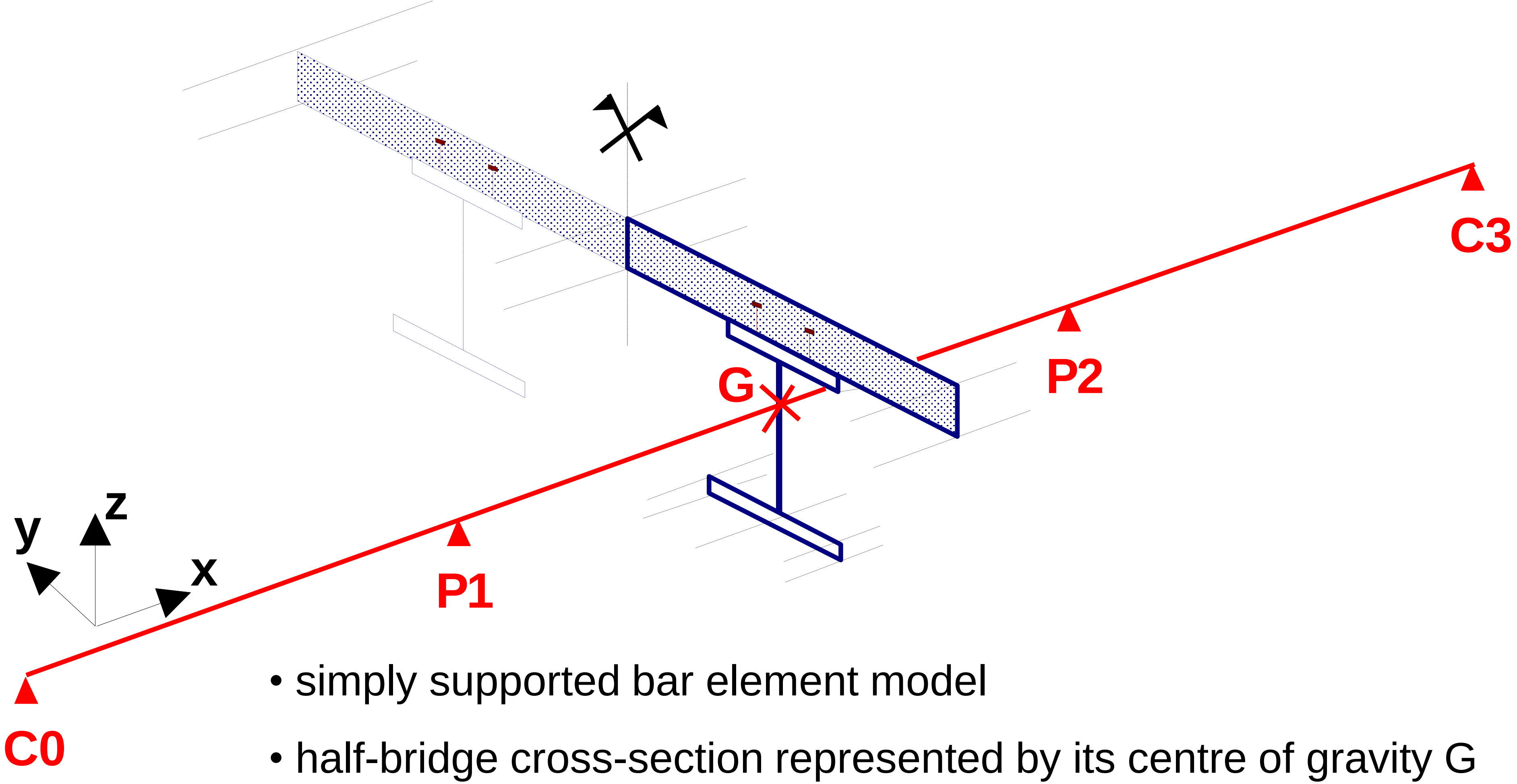
Global analysis of a composite bridge deck

1. Bridge deck modelling
   - Geometry and bridge structural behaviour
   - Effective width (shear lag effect)
   - Modular ratios (concrete creep)

→ Cross-sectional mechanical properties

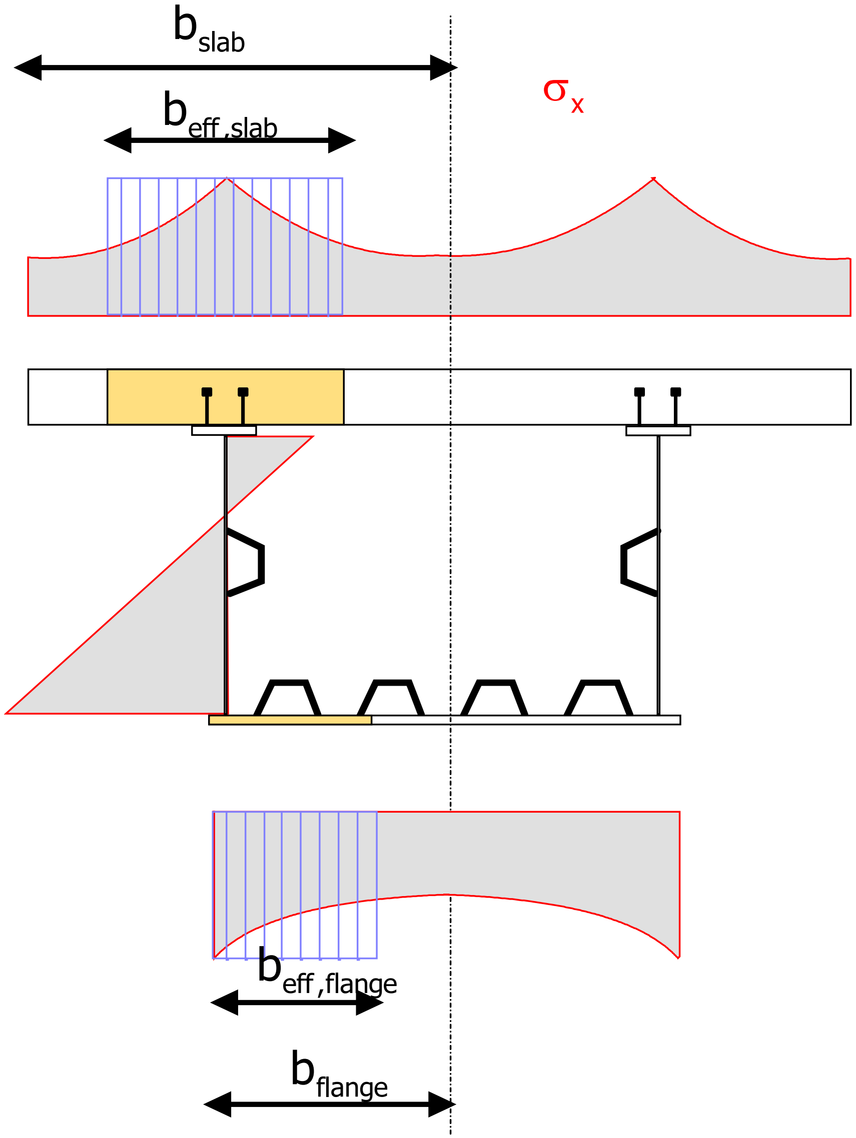
2. Apply the loads
   - Construction phases
   - Concrete shrinkage
   - Transversal traffic load distribution between main girders
3. Global cracked analysis according to EN 1994-2
   - Determination of the cracked zones around internal supports
   - Results from the global analysis

Twin-girder bridge modelling



- simply supported bar element model
- half-bridge cross-section represented by its centre of gravity G (neutral fibre)
- structural steel alone, or composite, mechanical properties according to the construction phases of the bridge slab

Shear lag in composite bridges



Concrete slab in EN 1994-2

Same effective^s width b_{eff} at SLS and ULS

Steel flange in EN 1993-1-5

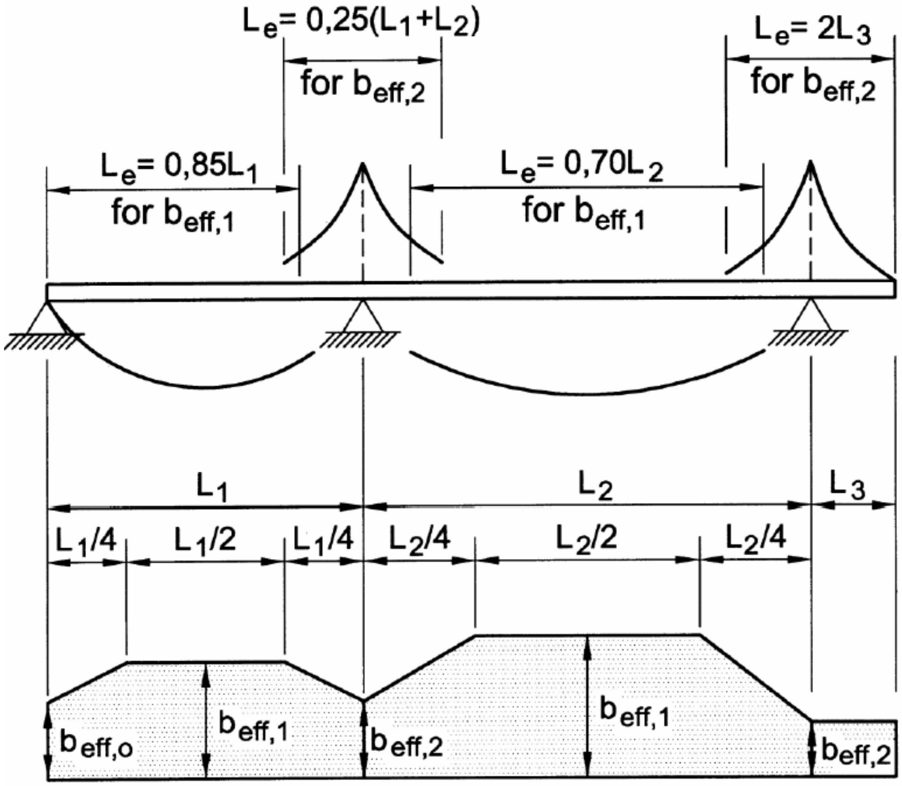
Used for the bottom flange of a box-girder bridge

Different effective^s width at SLS and ULS

Effective slab width in Eurocode 4

- **Equivalent span length L_e**

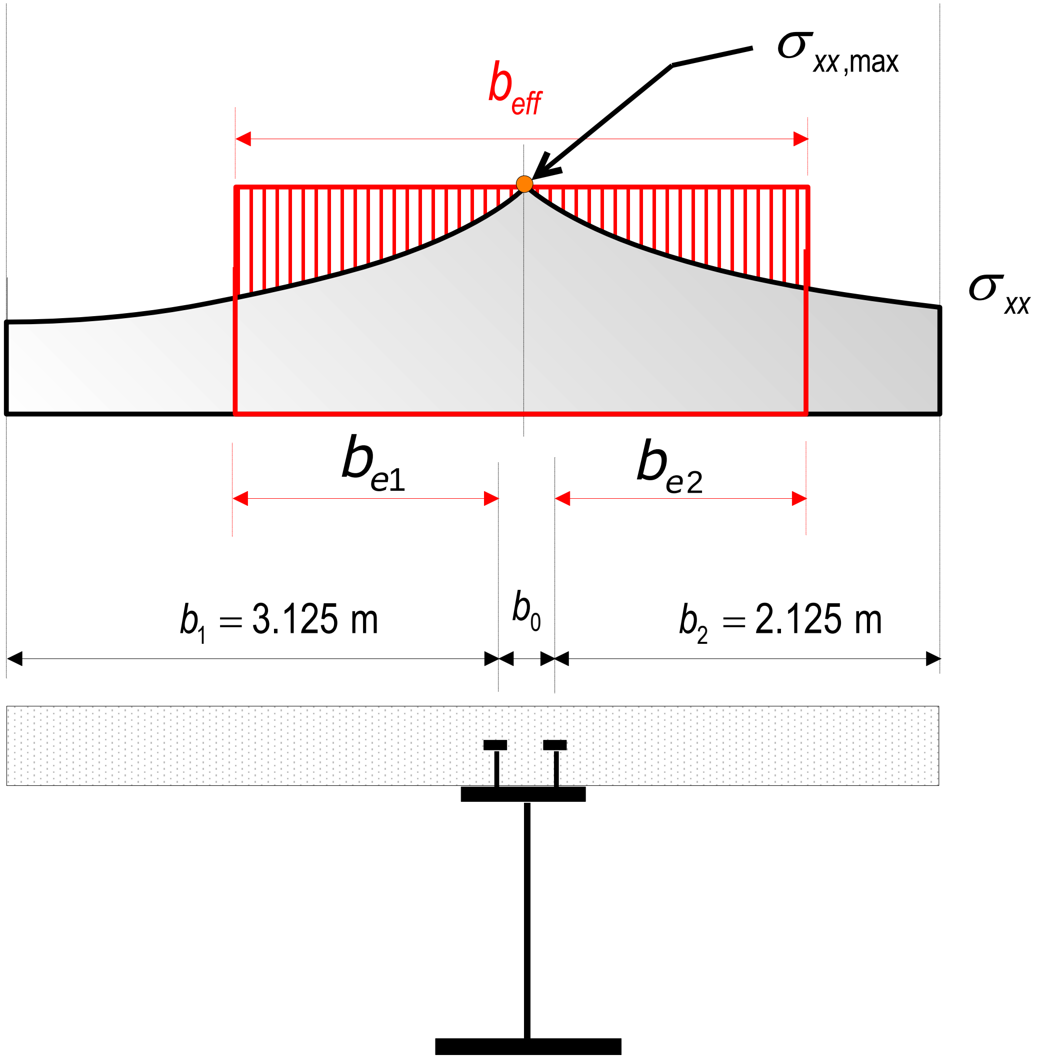
L_e is the approximate distance between points of zero bending moment.



- **Global analysis (determining internal forces and moments)** : effective width constant for each span (equal to the value at mid-span) for simplification

- **Section analysis (calculation of stresses)** : effective width linearly variable on both sides of the vertical supports over a length $L_i/4$

Shear lag in the concrete slab according to Eurocode 4



Non-uniform transverse distribution of the longitudinal stresses σ_{xx}

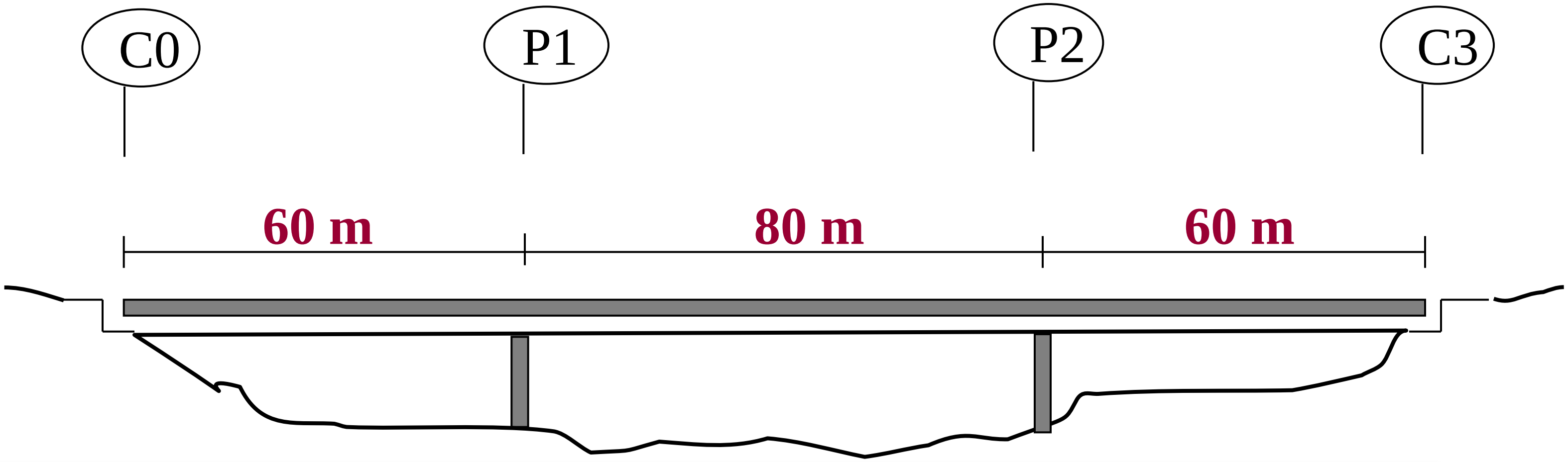
L_e equivalent span length

$$b_{ei} = \frac{L_e}{8} \leq b_i - \frac{b_0}{2}$$

$$b_0 = 750 \text{ mm}$$

$$b_{eff} = b_0 + \sum_i b_{ei}$$

Shear lag in the concrete slab according to Eurocode 4



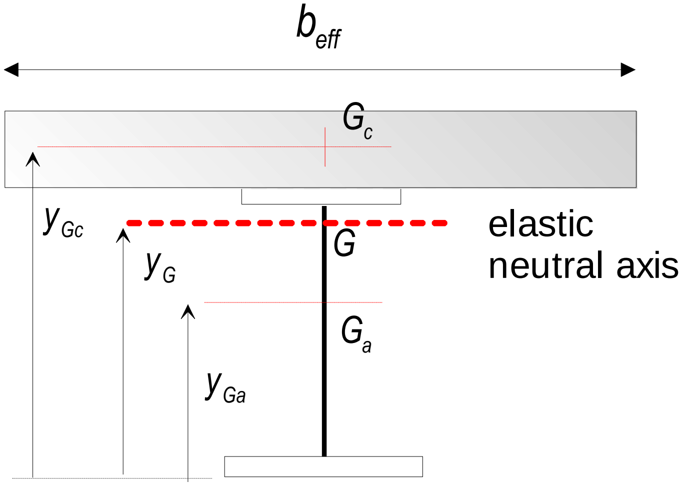
L_e (m)	0.85 x 60 = 51	0.7 x 80 = 56	0.85 x 60 = 51
	0.25 x (60+80) = 35		0.25 x (60+80) = 35

	L_e (m)	b_{e1} (m)	b_{e2} (m)	b_{eff} (m)
In-span 1 and 3	51	3.125	2.125	6.0
In-span 2	56	3.125	2.125	6.0
Internal supports P1 and P2	35	3.125	2.125	6.0

The concrete slab is fully effective (no reduction) because, for each steel main girder, its width (6 m) is small compared to the span length (60 m or 80 m).

Mechanical properties of the composite cross-sections

- **Un-cracked behaviour (mid-span regions: $M_{c,Ed} > 0$)**



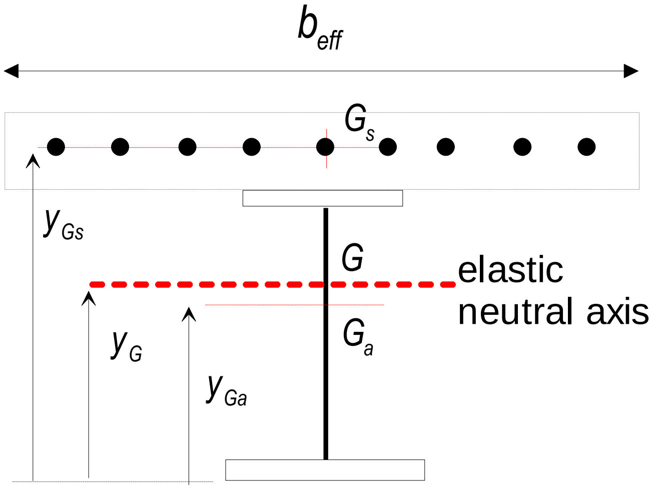
Reinforcement neglected (in compression)

$$A = A_a + \frac{A_c}{n} \qquad A y_G = A_a y_{Ga} + \frac{A_c}{n} y_{Gc}$$

$$I = I_a + A_a (y_G - y_{Ga})^2 + \frac{1}{n}\left[I_c + A_c (y_G - y_{Gc})^2 \right]$$

$n = E_a / E_c$ is the modular ratio between elasticity moduli.

- **Cracked behaviour (support regions: $M_{c,Ed} < 0$)**



$E_a = E_s = 210\,000$ N/mm²

$$A = A_a + A_s \qquad A y_G = A_a y_{Ga} + A_s y_{Gs}$$

$$I = I_a + A_a (y_G - y_{Ga})^2 + I_s + A_s (y_G - y_{Gs})^2$$

$$I_s \cong 0$$

Concrete creep effect : modular ratios

Short-term loading (no creep): $n_0 = \frac{E_a}{E_{cm}}$ with $E_{cm} = 22000(f_{cm}/10)^{0.3}$

Long-term loading (creep to be considered): $n_L = n_0(1+\psi_L \phi_t)$

$\phi_t = \phi(t - t_0)$ is the creep coefficient according to EN 1992 with :

t = age of concrete at the considered design date during the bridge life

t_0 = age of concrete when the considered loading is applied to the bridge

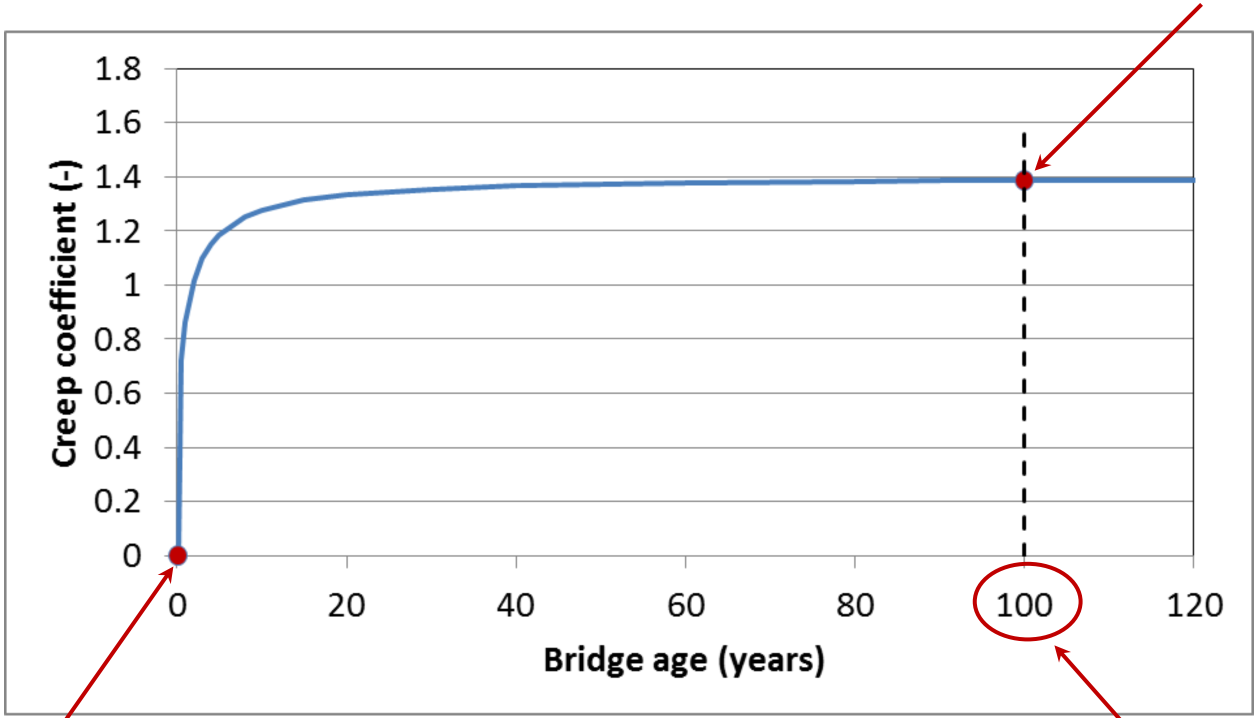
ψ_L depends on the load case:

Permanent loads	1.1
Shrinkage	0.55
Imposed deformations	1.5

Creep coefficient according to EN 1992

$$\phi_t = \phi\left(t_0, f_{cm}, RH, h_0\right)$$

$$\phi_\infty = \phi\left(\infty, t_0\right)$$



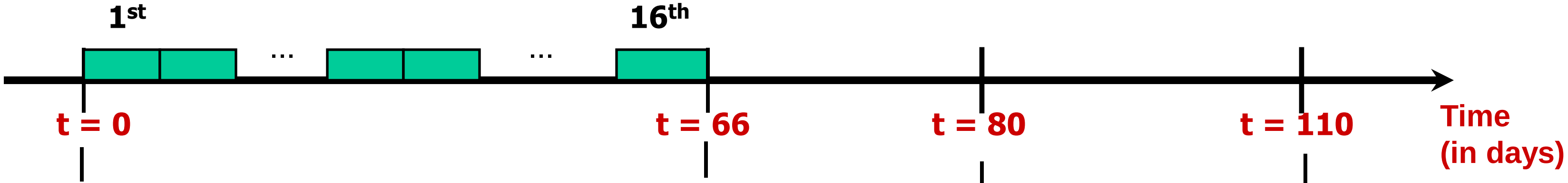
End of construction

All loading cases are applied to the bridge model using the short-term mechanical properties (n_0).

Design life of the bridge

Short-term loading : n_0
Long-term loading : n_L

Worked example: modular ratios



Phase 1	3			
Phase 2	8	5		
…	…	…	…	
Phase 16	66	63	…	3

Mean value of the ages of concrete segments :

$$t_0 = \frac{66 + 63 + \ldots + 3}{16 \text{ phases}} = 35.25 \text{ days}$$

used for all concreting phases
(simplification of EN1994-2).

$$\phi_1 = \phi\left(t = \infty, t_0\right)$$

$$n_{L,1} = n_0\left(1 + 1.1.\phi_1\right)$$

+ 14 days →

$$t_0 = 49.25 \text{ days}$$

$$\phi_2 = \phi\left(\infty, t_0\right)$$

$$n_{L,2} = n_0\left(1 + 1.5.\phi_2\right)$$

+ 30 days →

$$t_0 = 79.25 \text{ days}$$

$$\phi_3 = \phi\left(\infty, t_0\right)$$

$$n_{L,3} = n_0\left(1 + 1.1.\phi_3\right)$$

Note : t_0 = 1 day when shrinkage is applied to a concrete segment.

$$\phi_4 = \phi\left(\infty, t_0\right) \qquad n_{L,4} = n_0\left(1 + 0.55.\phi_4\right)$$

Worked example: modular ratios

- **Short-term loading :**

$$n_0 = \frac{E_a}{E_{cm}} = 6.2$$

- **Long-term loading (permanent loads, shrinkage, imposed deformations) :**

Load case	ψ_L	t_0 (days)	$\phi_t = \phi_0$	n_L
Concrete slab segment (selfweight)	1.10	35.25	1.39	**15.6**
Settlement	1.50	49.25	1.29	**18.1**
Shrinkage	0.55	1	2.68	**15.2**
Bridge equipments (safety barriers, road pavement,…)	1.10	79.25	1.18	**14.1**

Global analysis of a composite bridge deck

1. Bridge deck modelling
   - Geometry and global bridge behaviour
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   - Modular ratios (concrete creep)

→ Cross-sectional mechanical properties

2. Apply the loads
   - Construction phases
   - Concrete shrinkage
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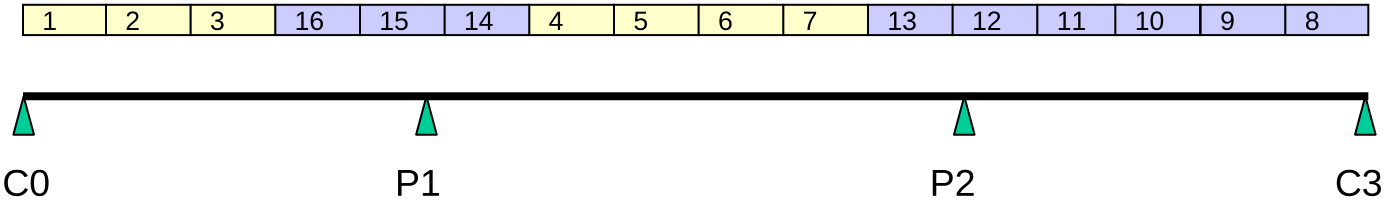
Applied loads for the road bridge example

Permanent loads (taking creep into account if relevant)		
G_{max} , G_{min}	Self weight: • structural steel • concrete (by segments in a selected order) • non structural equipments (safety barriers, pavement,…)	EN1991 part 1-1
S	Shrinkage (drying, autogenous and thermal shrinkage strains)	EN1992 part 1-1 EN1994 part 2
P	Pre-stressing by imposed deformations (for instance, jacking on internal supports)	
Variable loads (no creep effect)		
T_k	Temperature effects	EN1991 part 1-5
UDL, TS	Road traffic	EN1991 part 2
FLM3	Fatigue load model (for instance, the equivalent lorry FLM3)	EN1991 part 2

Construction slab stages

- imposed concreting order to reduce the concrete tension around internal supports
- For the example, 16 concreting phases (12.5 m long slab segment)



1	2	3	16	15	14	4	5	6	7	13	12	11	10	9	8

C0 P1 P2 C3

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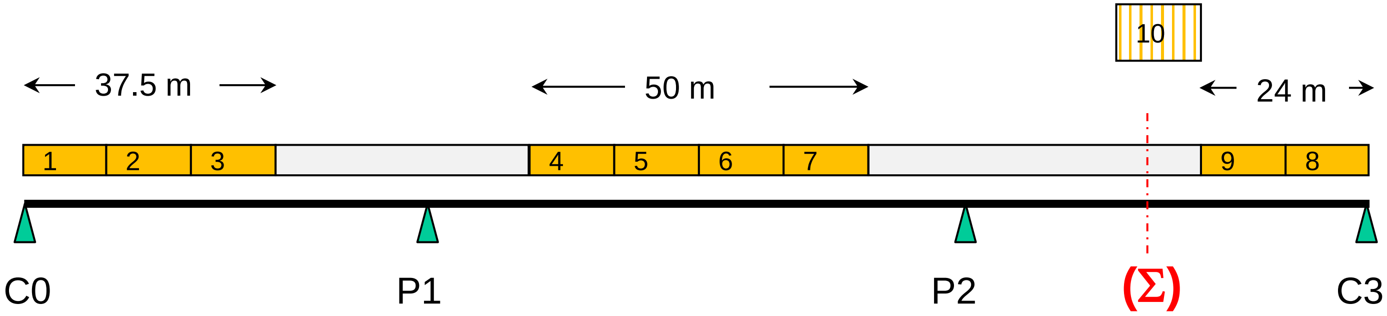
Construction slab stages

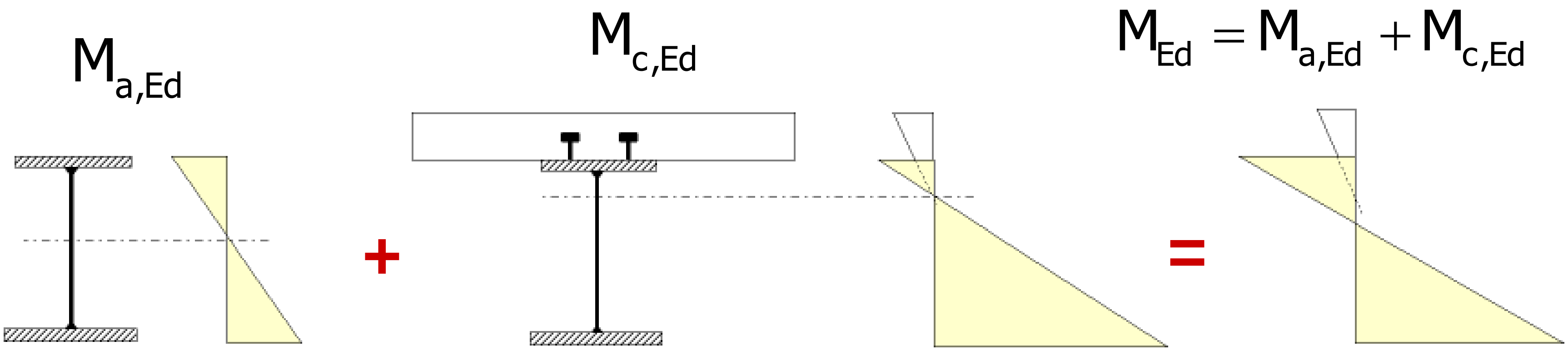
During the 10th concreting phase, the load case is the self-weight of the 10th concrete segment.



🟨 Mechanical properties of the composite un-cracked cross-section

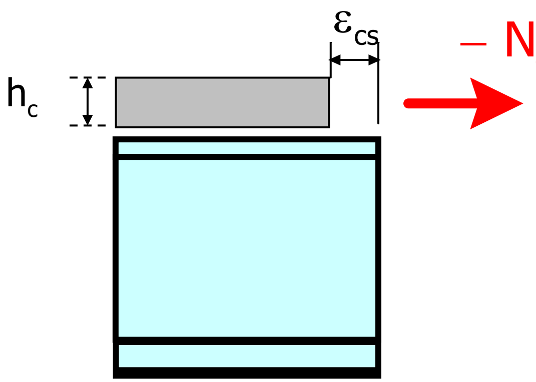
⬜ Mechanical properties of the structural steel alone cross-section

In the cross-section (Σ), the stress distribution should take into account the construction history.



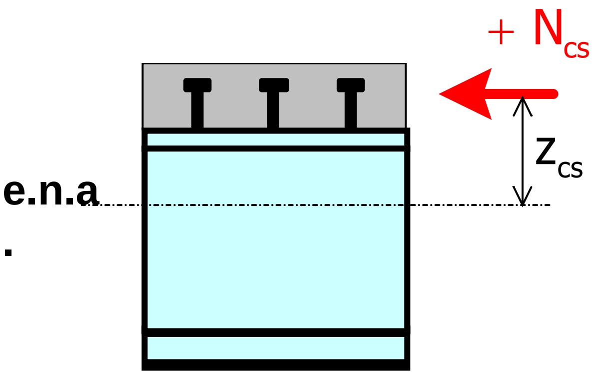
$$M_{Ed} = M_{a,Ed} + M_{c,Ed}$$

Effects of shrinkage in a composite bridge



$$-N_{cs} = -E_c \varepsilon_{cs}.b_c h_c$$

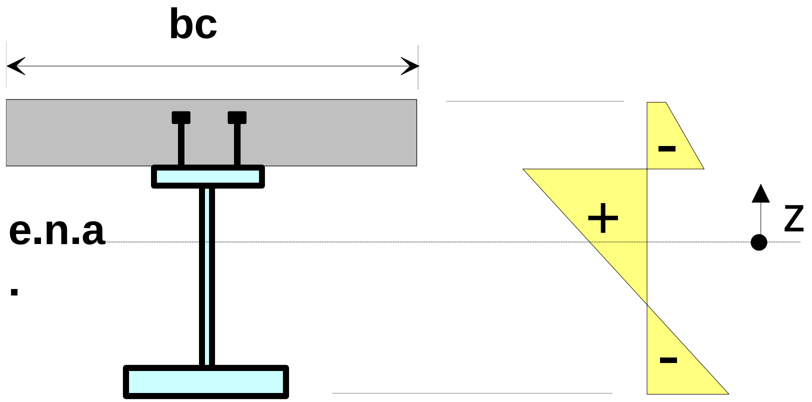
+



Free shrinkage strain applied on concrete slab only (no steel – concrete interaction)

Shrinkage strain applied on the composite section (after steel – concrete interaction)

1- Auto-equilibrated stress diagram in every section and an imposed rotation due to the bending moment $M_{iso} = N_{cs} z_{cs}$:

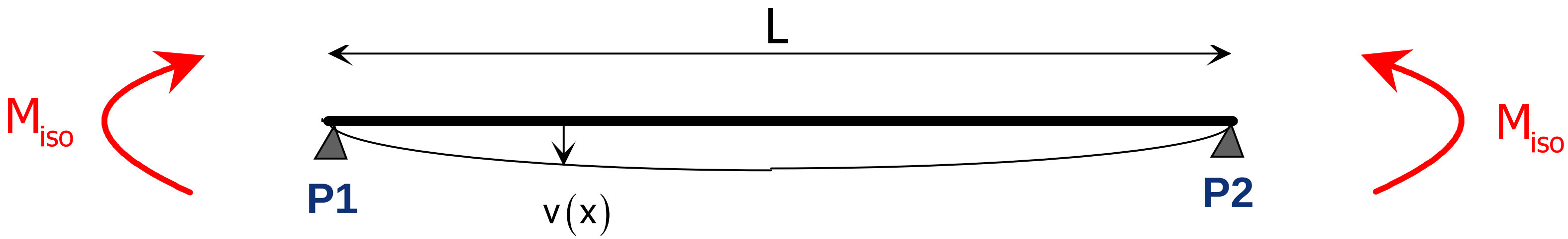


$$\sigma_{concrete} = -E_c \varepsilon_{cs} + \frac{1}{n}.\left[\frac{N_{cs}}{A} + \frac{(N_{cs} z_{cs}).z}{I}\right]$$

$$\sigma_{steel} = \frac{N_{cs}}{A} + \frac{(N_{cs} z_{cs}).z}{I}$$

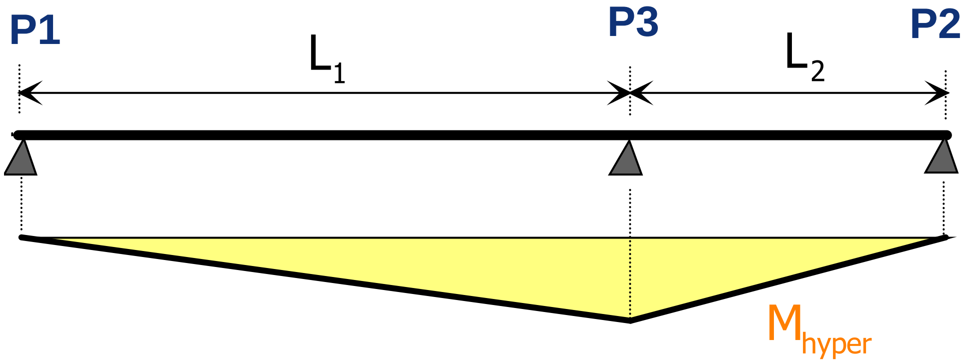
Effects of shrinkage in a composite bridge

2- Curvature in an isostatic bridge due to the imposed deformations :



3- Compatibility of deformations to be considered in an hyperstatic bridge :

$v(P3) = 0$

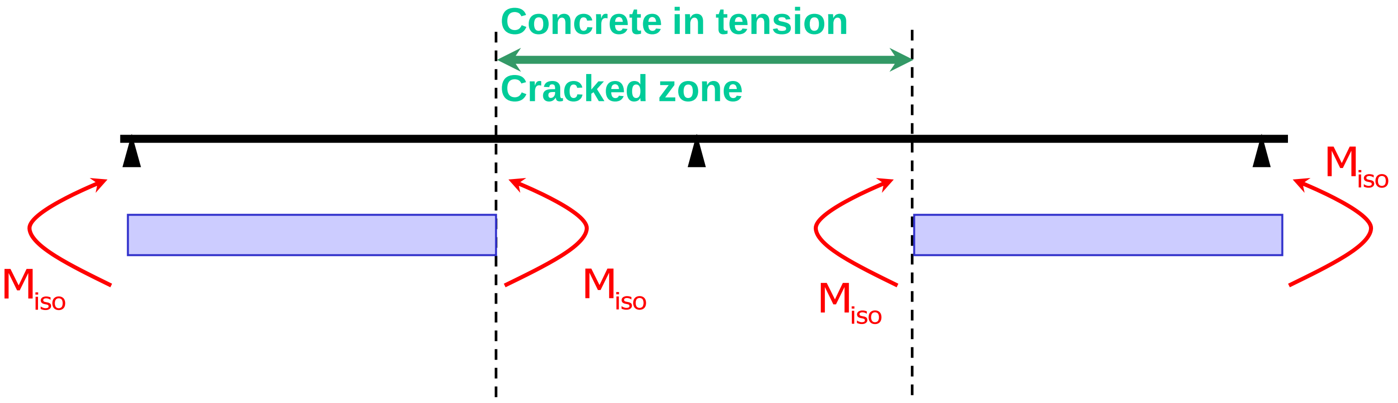


Effects of shrinkage

1+2 = ***isostatic*** (or ***primary***) effects

3 = ***hyperstatic*** (or ***secondary***) effects

Shrinkage and cracked global analysis

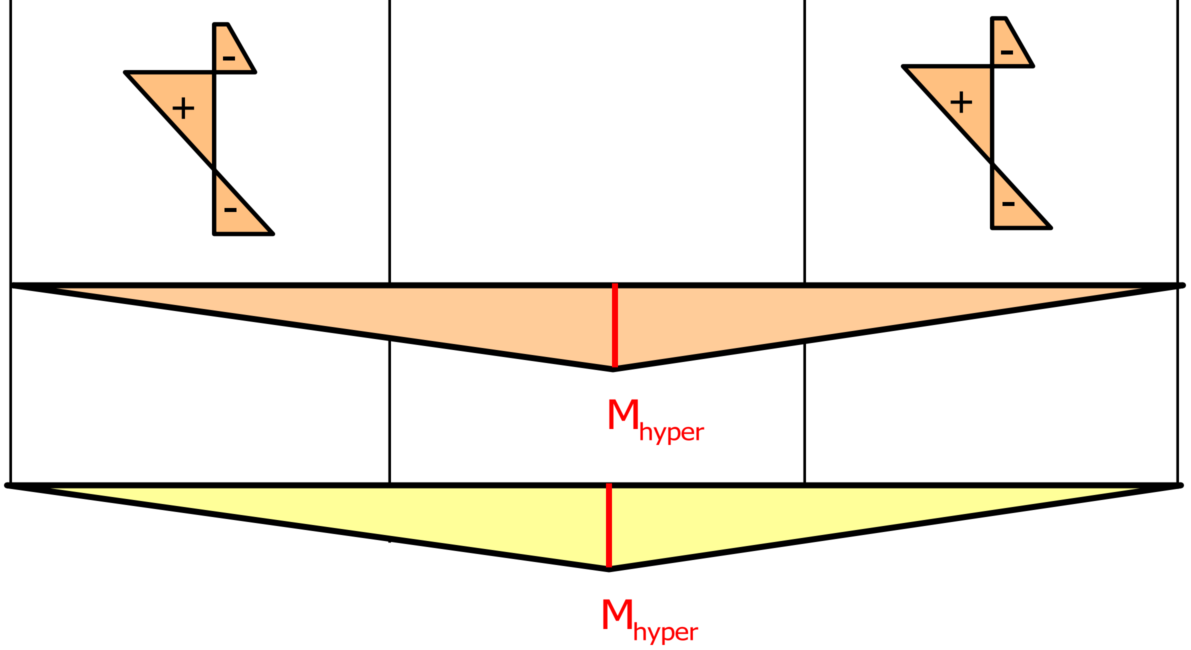


Isostatic effects neglected in cracked zones for calculating hyperstatic effects

SLS combinations	iso + hyper effects	hyper	iso + hyper
ULS combinations	hyper (if class 1)	hyper	Hyper (if class 1)

Serviceability Limit State

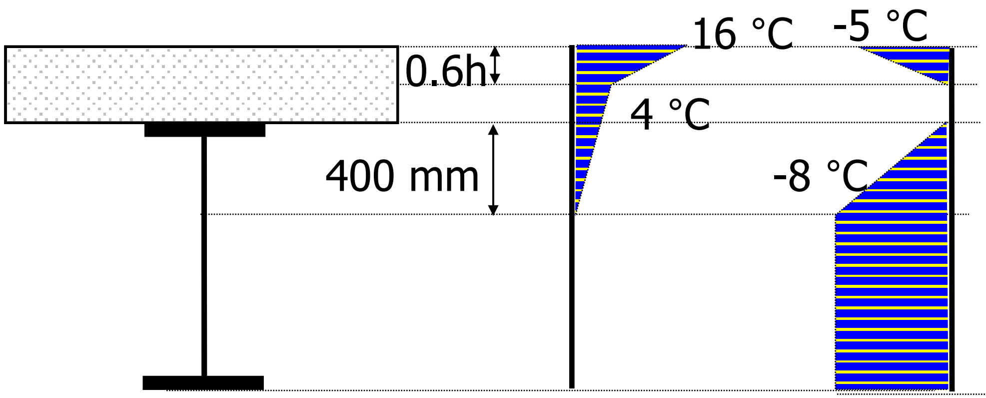
Ultimate Limit State



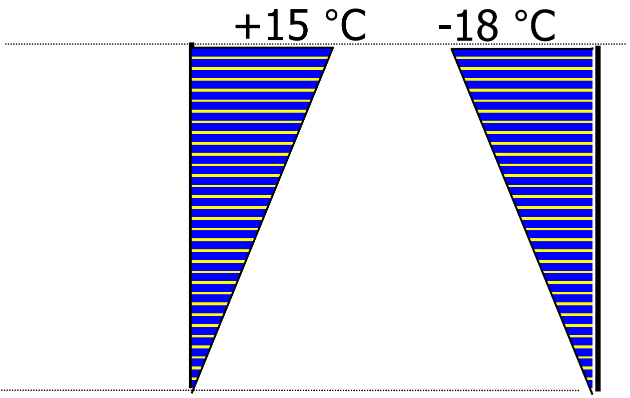
Thermal gradient from Eurocode 1 Part 1-5

- could be neglected if all cross-sections are in Class 1 or 2
- 3 options: have to be chosen in the National Annex

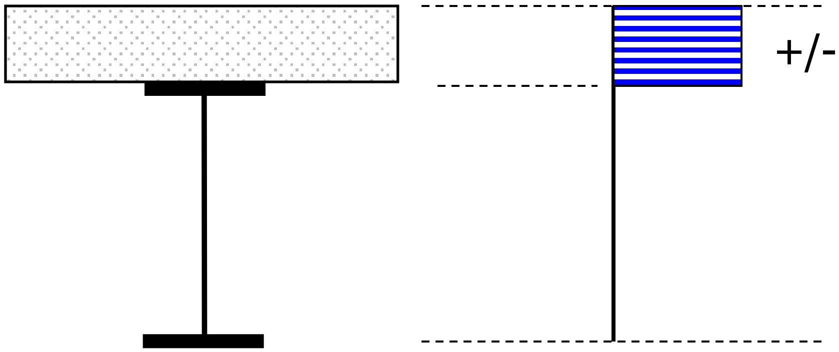
1- Non linear gradients :



2- Linear gradients :

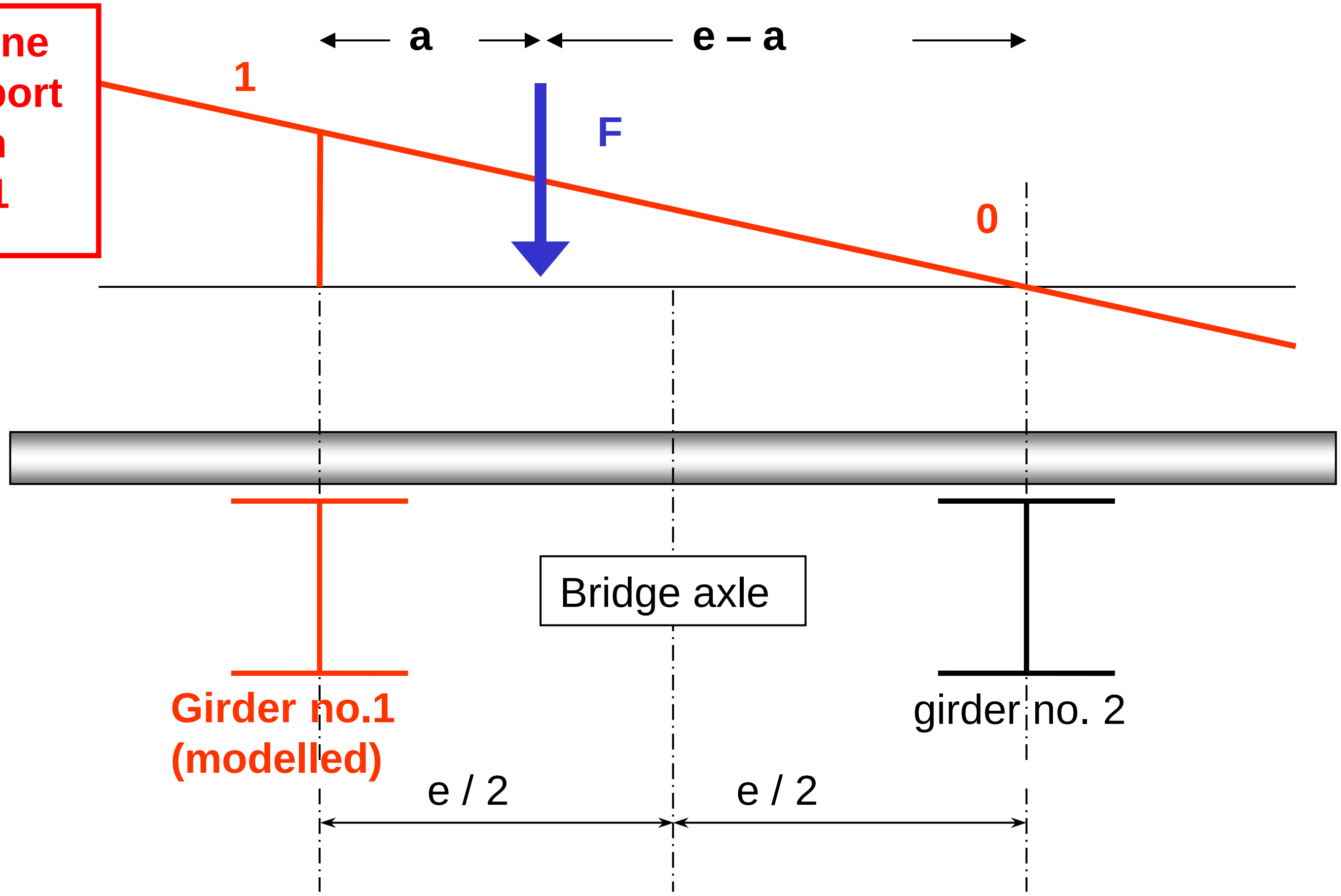


3- Difference +/- 10 °C :



Transversal distribution of live load between the two girders

Influence line of the support reaction on girder no. 1

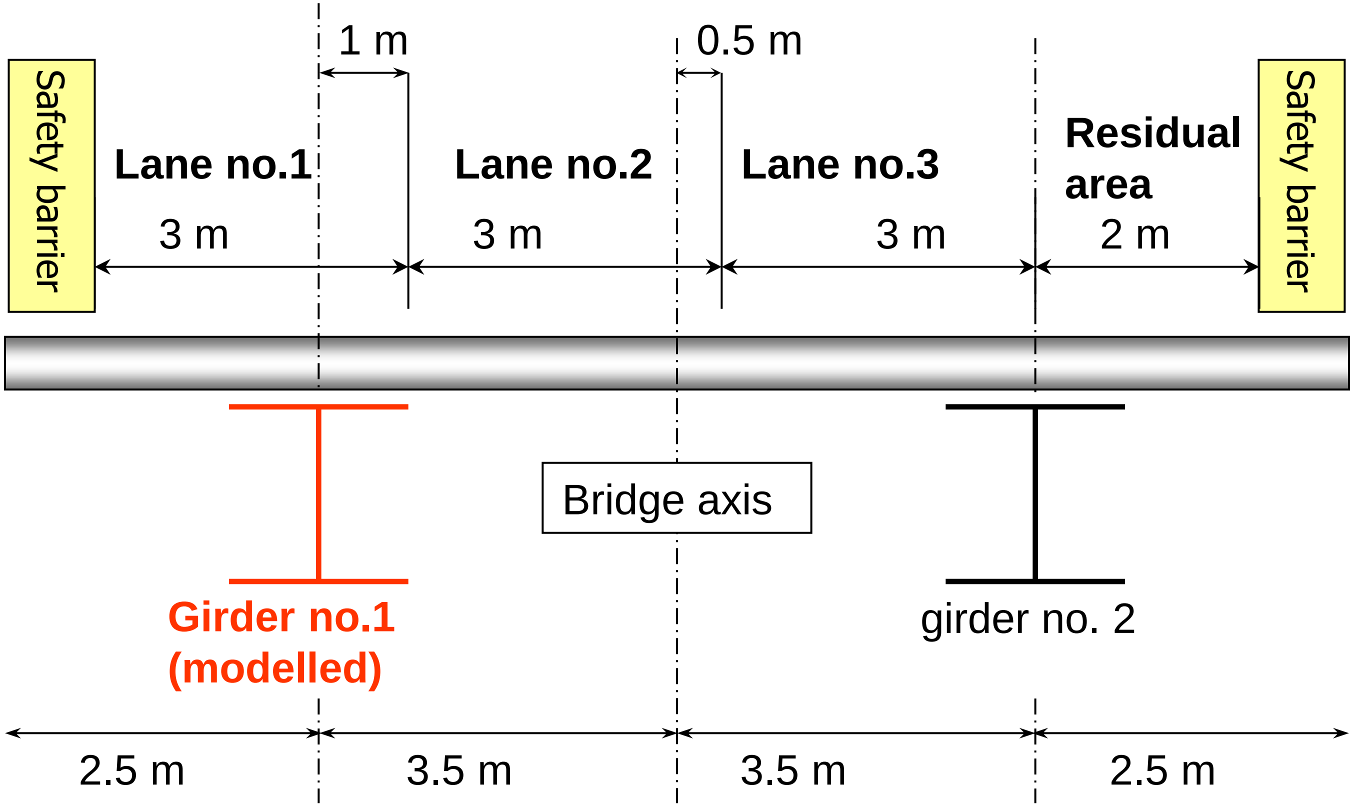


$$R_1 = F\left(1 - \frac{a}{e}\right) \qquad R_2 = F\frac{a}{e}$$

No warping stress calculations and slab torsional stiffness neglected

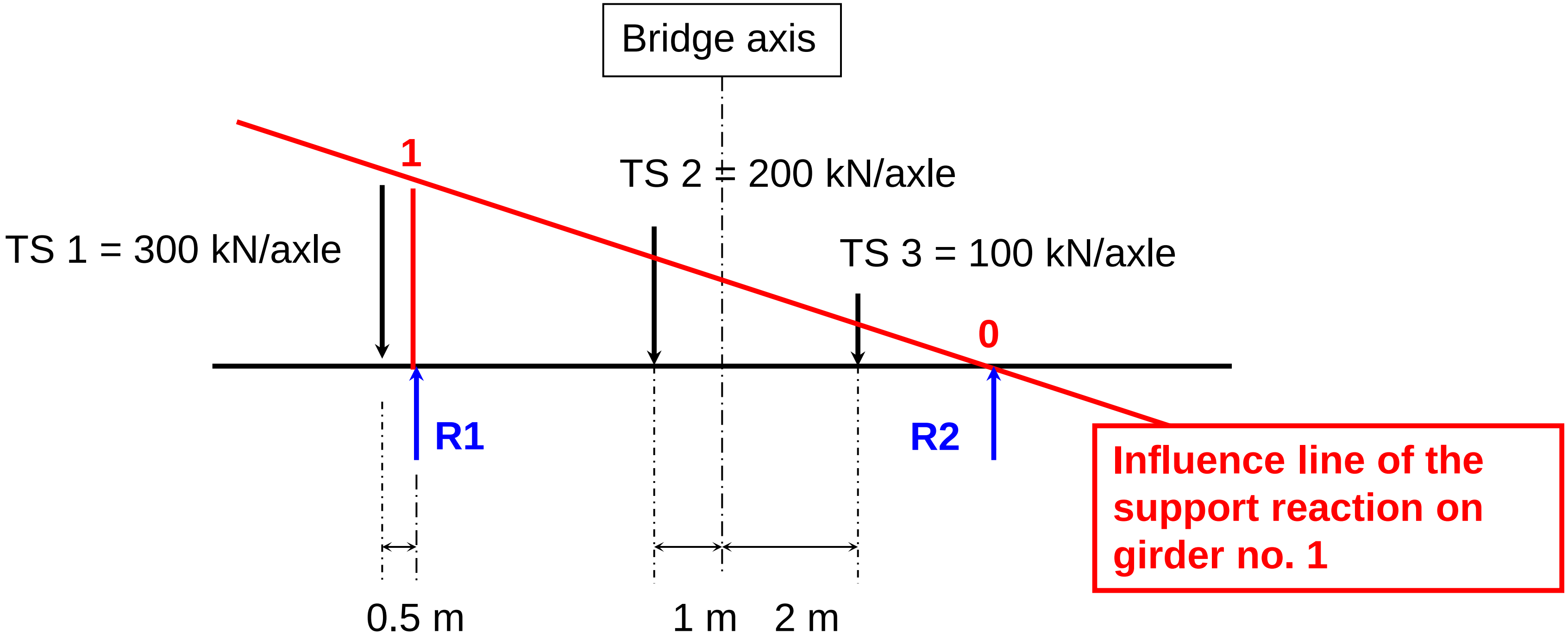
Application to the traffic load model LM1

1. Conventional traffic lanes positioning



Application to the traffic load model LM1

2. Tandem System TS



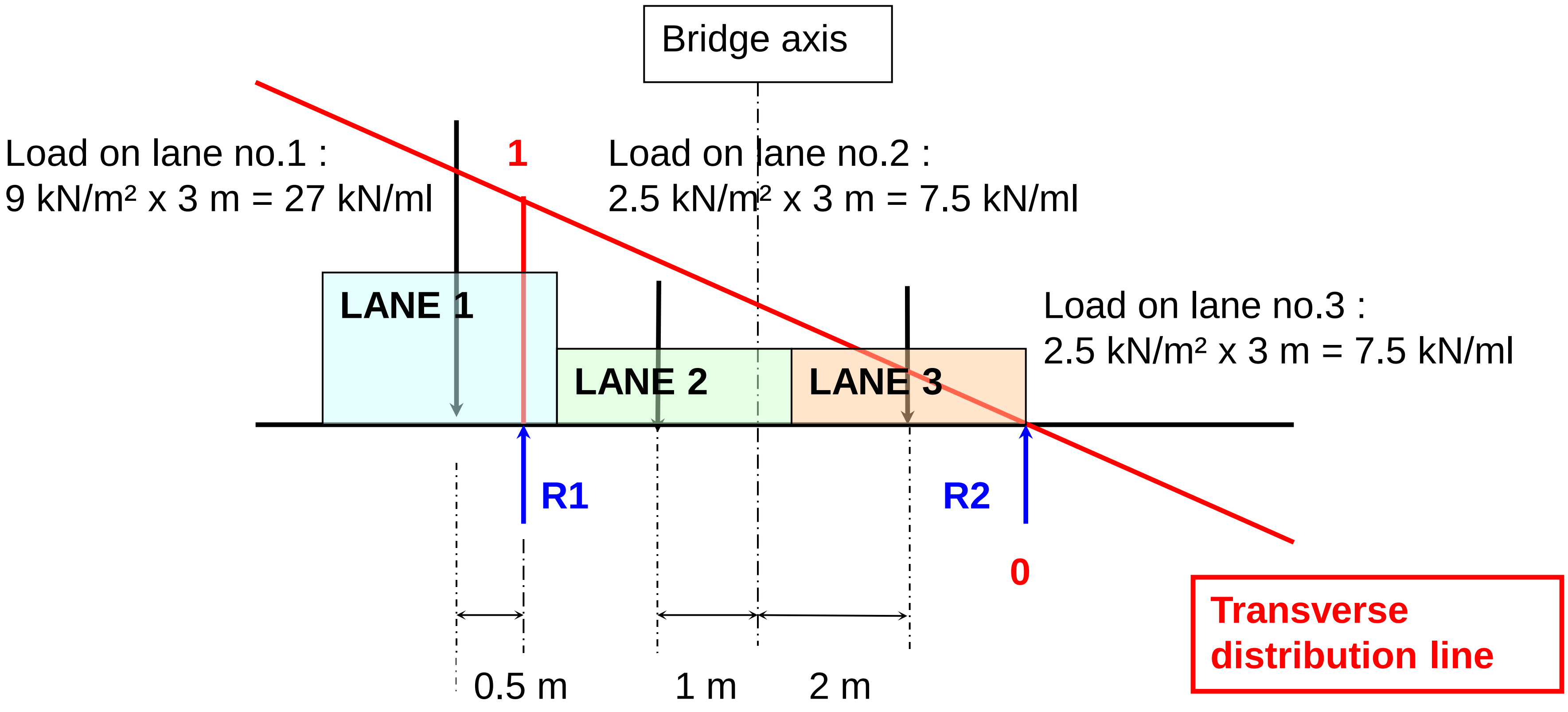
Influence line of the support reaction on girder no. 1

Support reaction on each main girder : $R_1 = 471.4$ kN

$R_2 = 128.6$ kN

Application to the traffic load model LM1

3. Uniform Design Load UDL

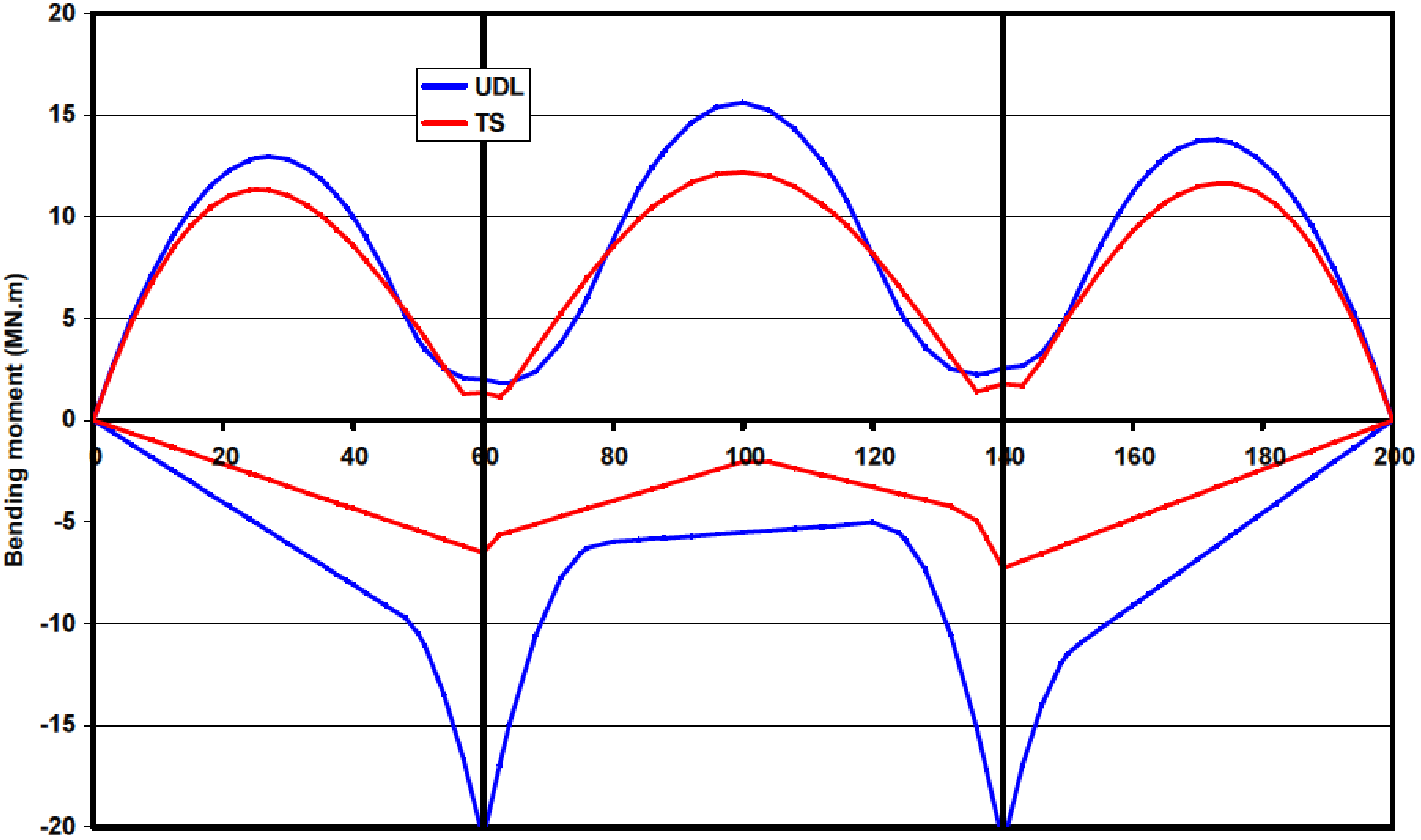


Support reaction for each main girder : $R_1 = 35.36$ kN/ml

$R_2 = 6.64$ kN/ml

Application to the traffic load model LM1

4. Bending Moment (MN.m) for UDL and TS



Combinations of actions

For every **permanent design situation**, two limit states of the bridge should be considered :

⇨ Serviceability Limit States (SLS)

- **Quasi permanent SLS**

  $G_{max} + G_{min} + S + P + 0.5\ T_k$

- **Frequent SLS**

  $G_{max} + G_{min} + S + P + 0.75\ TS + 0.4\ UDL + 0.5\ T_k$

  $G_{max} + G_{min} + S + P + 0.6\ T_k$

- **Characteristic SLS**

  $G_{max} + G_{min} + S + P + (TS+UDL) + 0.6\ T_k$

  $G_{max} + G_{min} + S + P + Q_{lk} + 0.75\ TS + 0.4\ UDL + 0.6\ T_k$

  $G_{max} + G_{min} + S + P + T_k + 0.75\ TS + 0.4\ UDL$

⇨ Ultime Limite State (ULS) other than fatigue

$\mathbf{1.35}\ G_{max} + G_{min} + S + P + \mathbf{1.35}\ (TS + UDL) + \mathbf{1.5}\ (0.6\ T_k)$

$\mathbf{1.35}\ G_{max} + G_{min} + S + P + \mathbf{1.35}\ Q_{lk} + \mathbf{1.35}\ (0.75\ TS + 0.4\ UDL) + \mathbf{1.5}\ (0.6\ T_k)$

$\mathbf{1.35}\ G_{max} + G_{min} + S + P + \mathbf{1.5}\ T_k + \mathbf{1.35}\ (0.75\ TS + 0.4\ UDL)$

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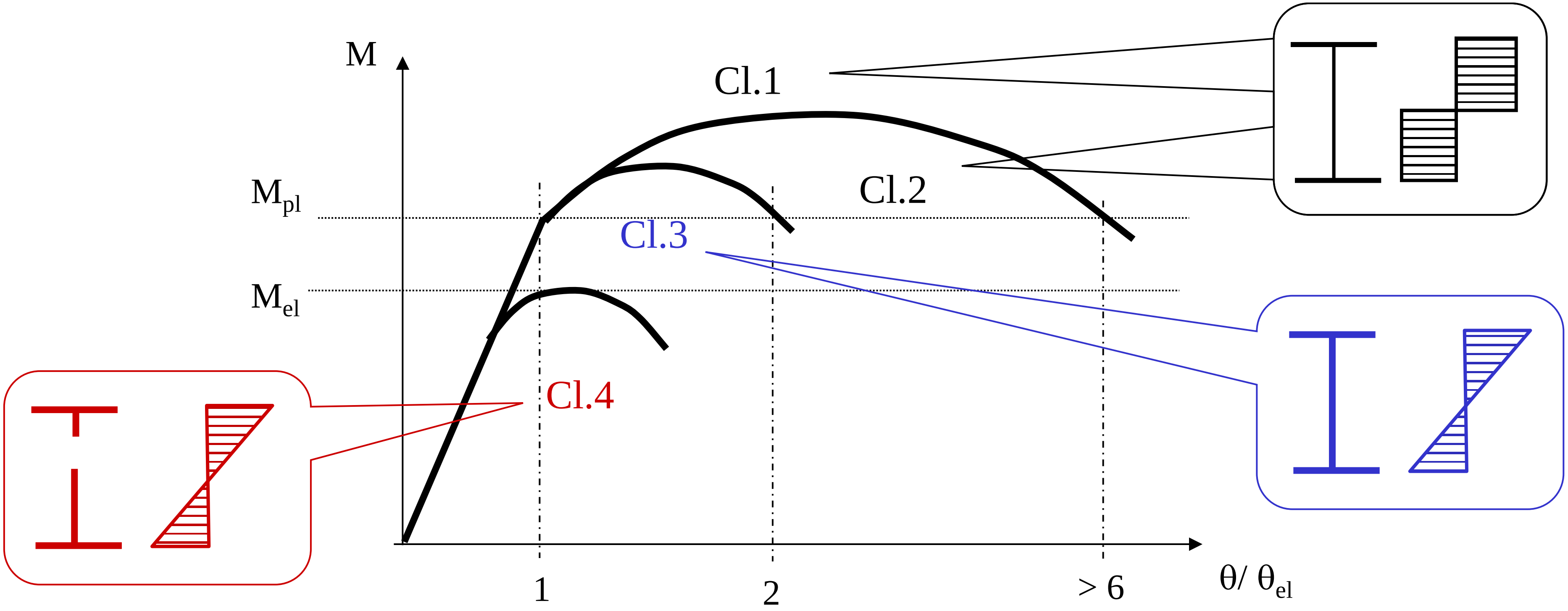
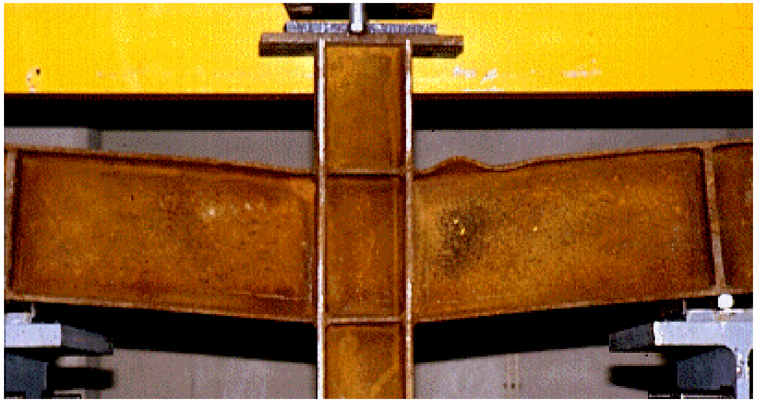
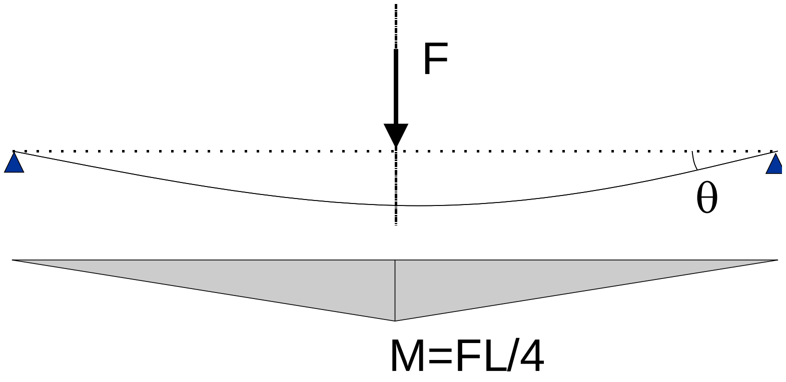
Classification of cross-sections (EC3)



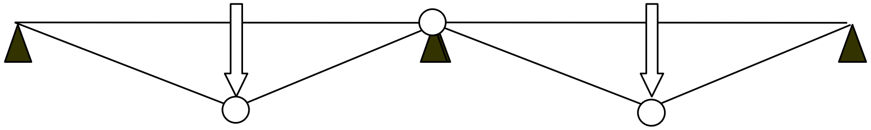




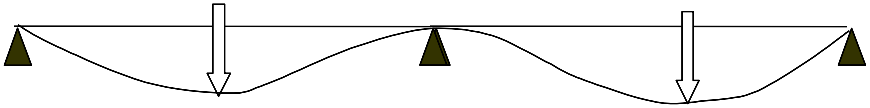
Classification of cross-sections

CLASS 1 sections which can form a plastic hinge with the rotation capacity required for a global plastic analysis

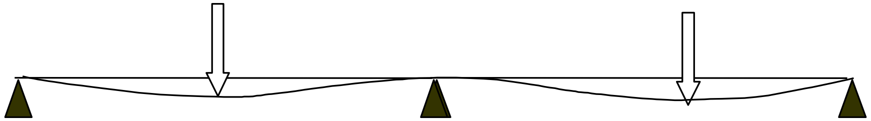
Not for bridges
Except accidental
design situation

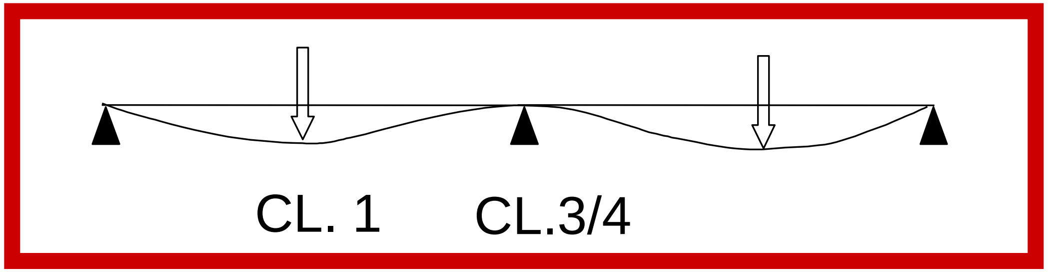


CLASS 2 sections which can develop $M_{pl,Rd}$ with limited rotation capacity



CLASS 3 sections which can develop $M_{el,Rd}$

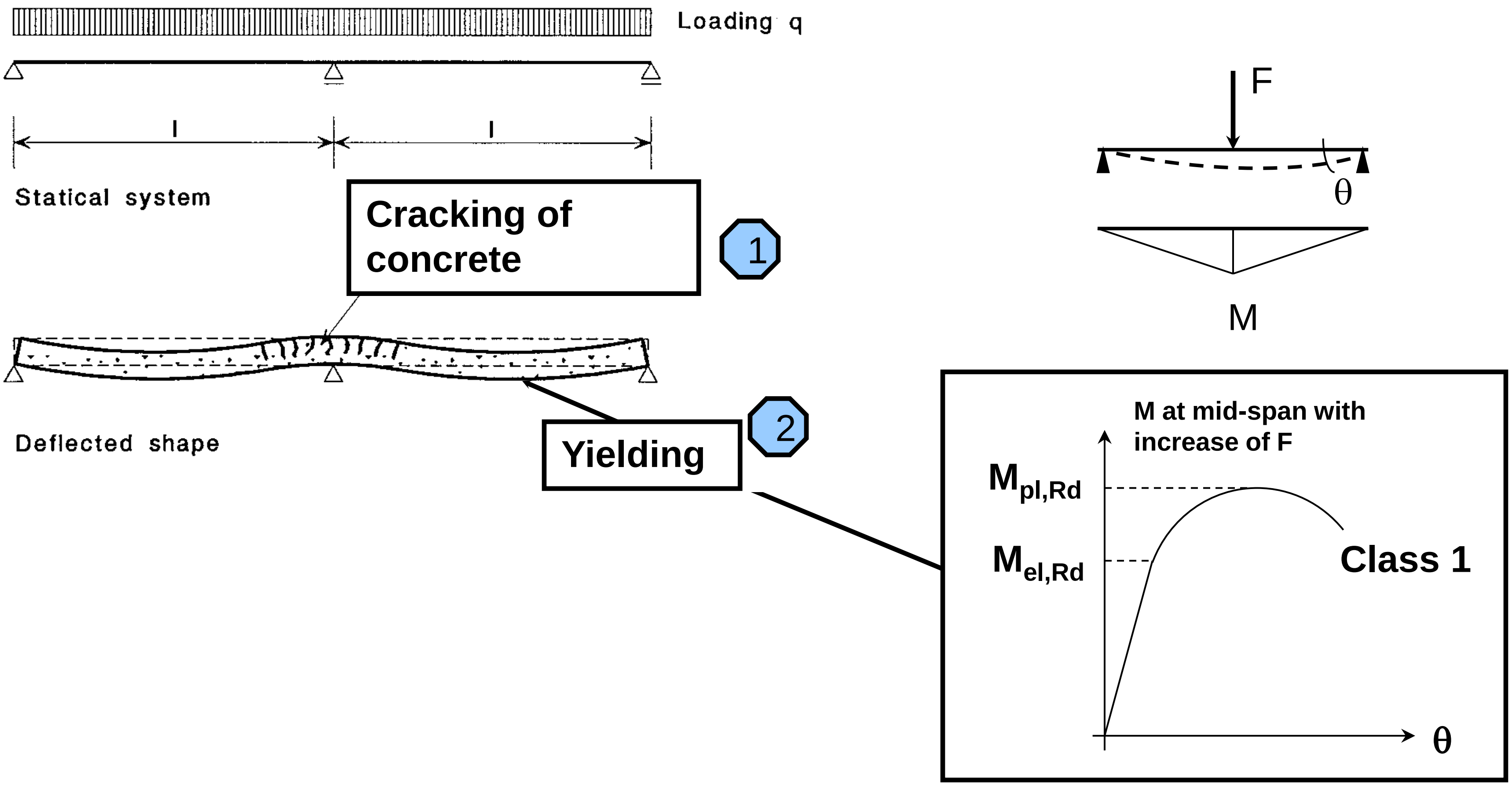




COMPOSITE BRIDGES
Non-uniform section
(except for small spans)

Actual behaviour of a composite bridge

When performing the elastic global analysis, two aspects of the non-linear behaviour are indirectly considered.



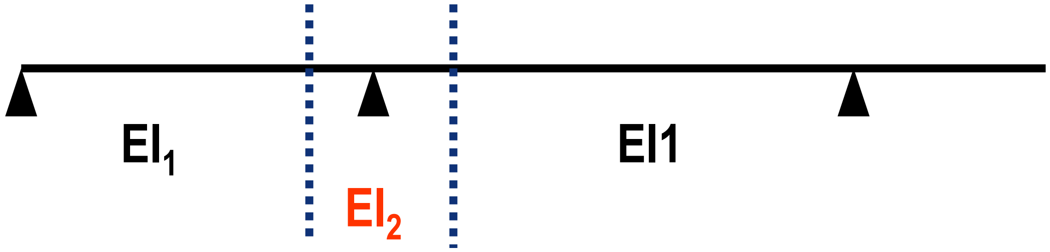
Cracking of concrete ①

Yielding ②

Cracked global analysis

1

- Determination of the stresses σ_c in the extreme fibre of the concrete slab under SLS characteristic combination according to a non-cracked global analysis
- In sections where $\sigma_c < -2 f_{ctm}$, the concrete is assumed to be cracked and its resistance is neglected



EI_1 = un-cracked composite inertia (structural steel + concrete in compression)

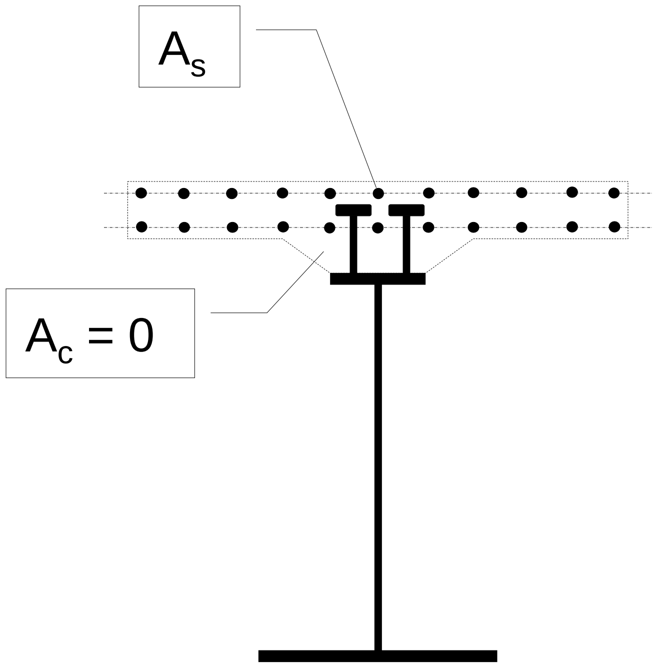
EI_2 = cracked composite inertia (structural steel + reinforcement)

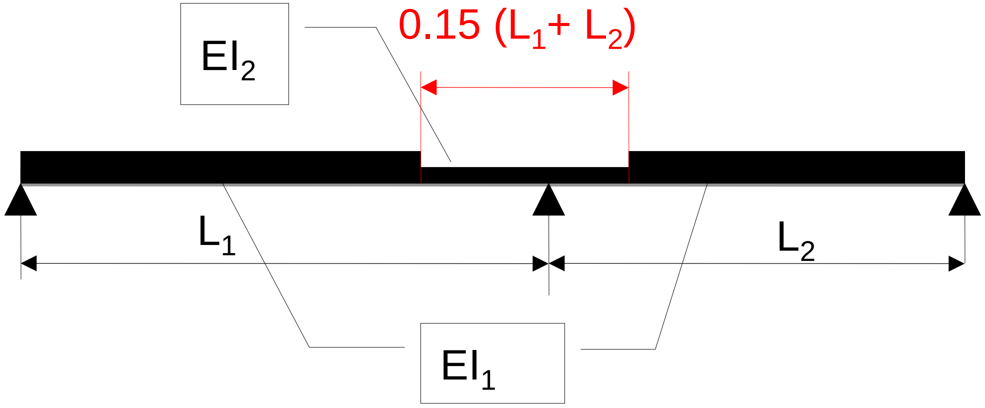
No iteration is needed !

Cracked global analysis

Simplified method usable if :

- no pre-stressing by imposed deformation
- $L_{min}/L_{max}>0.6$



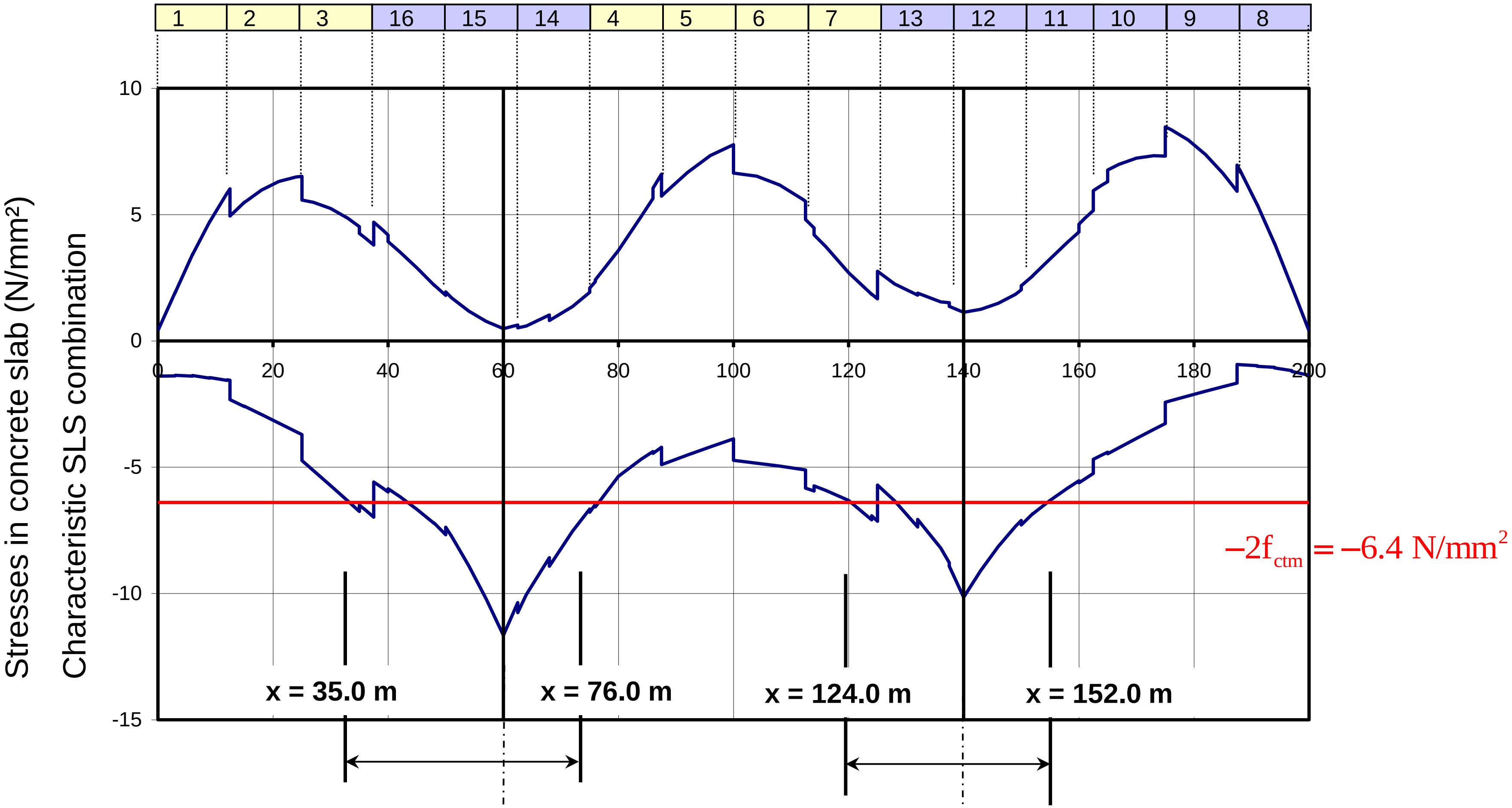


In the cracked zones EI_2 :

- the resistance of the concrete in tension is neglected
- the resistance of the reinforcement is taken into account

Worked example: Cracked zones around internal supports

Stresses calculated including the construction phasing and the un-cracked composite behaviour



$-2f_{ctm} = -6.4\ \mathrm{N/mm^2}$

Cracked zone for P1

41.0 % **19.5 %**

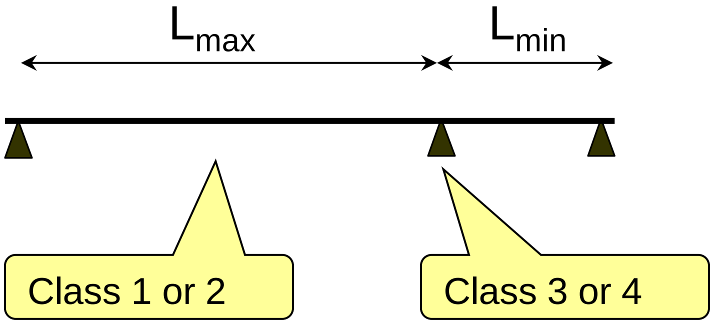
Cracked zone for P2

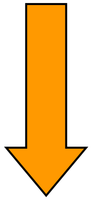
19.5 % **20.0 %**

Yielding

Yielding at mid-span induces bending redistribution which should be considered if :

- Class 1 or 2 cross-section at mid-span (and $M_{Ed} > M_{el,Rd}$)
- Class 3 or 4 near intermediate support
- $L_{min}/L_{max} < 0.6$





- Elastic linear analysis with an additional verification for the cross-sections in sagging bending zone (M>0) :

$$\mathbf{M_{Ed} < 0.9\ M_{pl,Rd}}$$

or

- Non linear global analysis (Finite Elements for instance)

Global analysis - Synthesis

To calculate the internal forces and moments for the ULS combination of actions

- elastic global analysis (except for accidental loads)
- cracking of the concrete slab
- shear lag (in the concrete slab : L_e/8 constant value for each span)
- neglecting plate buckling (except for an effective^p area of an element $\leq$ 0.5 * gross area)

To calculate the internal forces and moments for the SLS combinations of actions

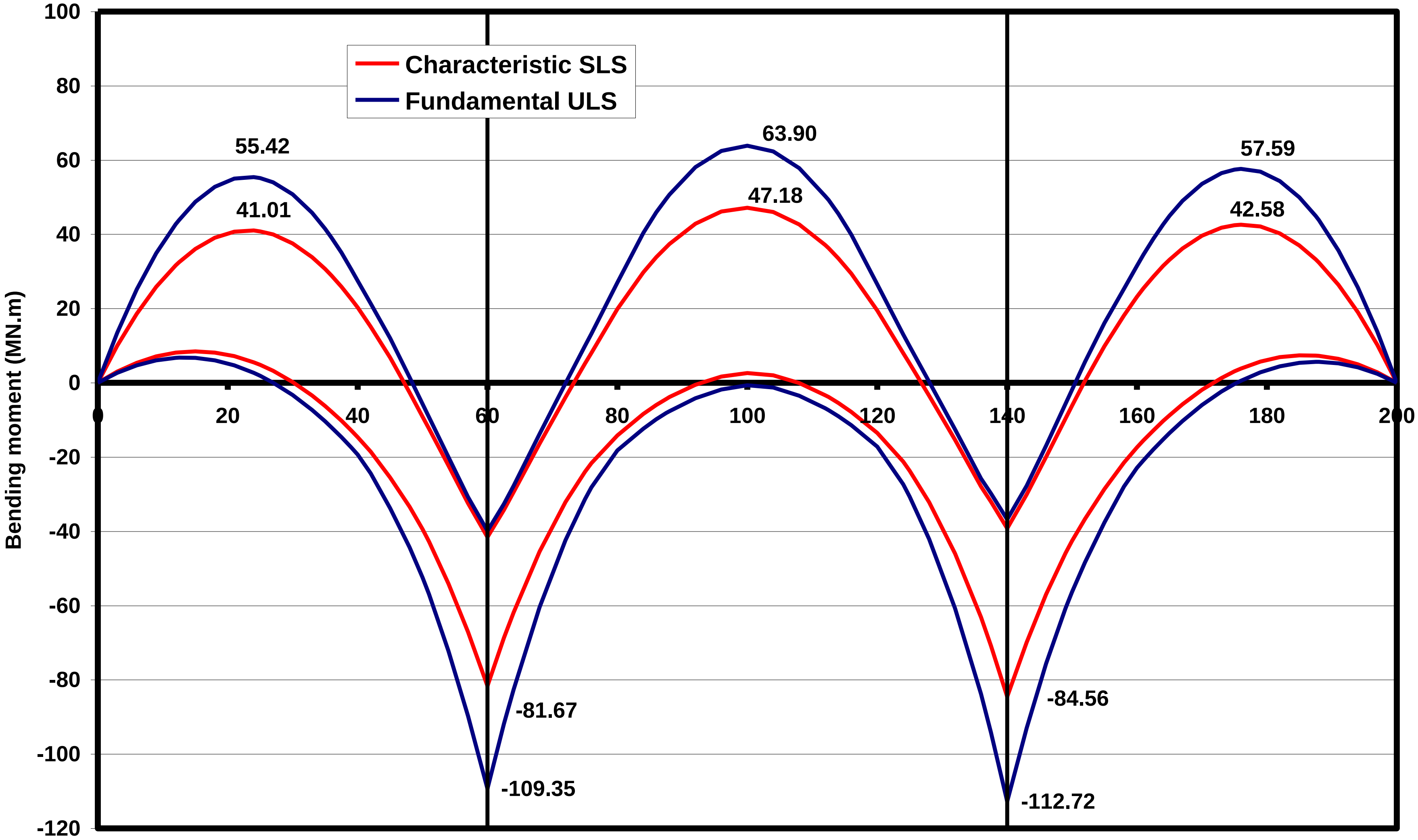
- as for ULS

To calculate the longitudinal shear per unit length (SLS and ULS) at the steel-concrete interface

- Cracked global analysis, elastic and linear
- *Always* un-cracked section analysis

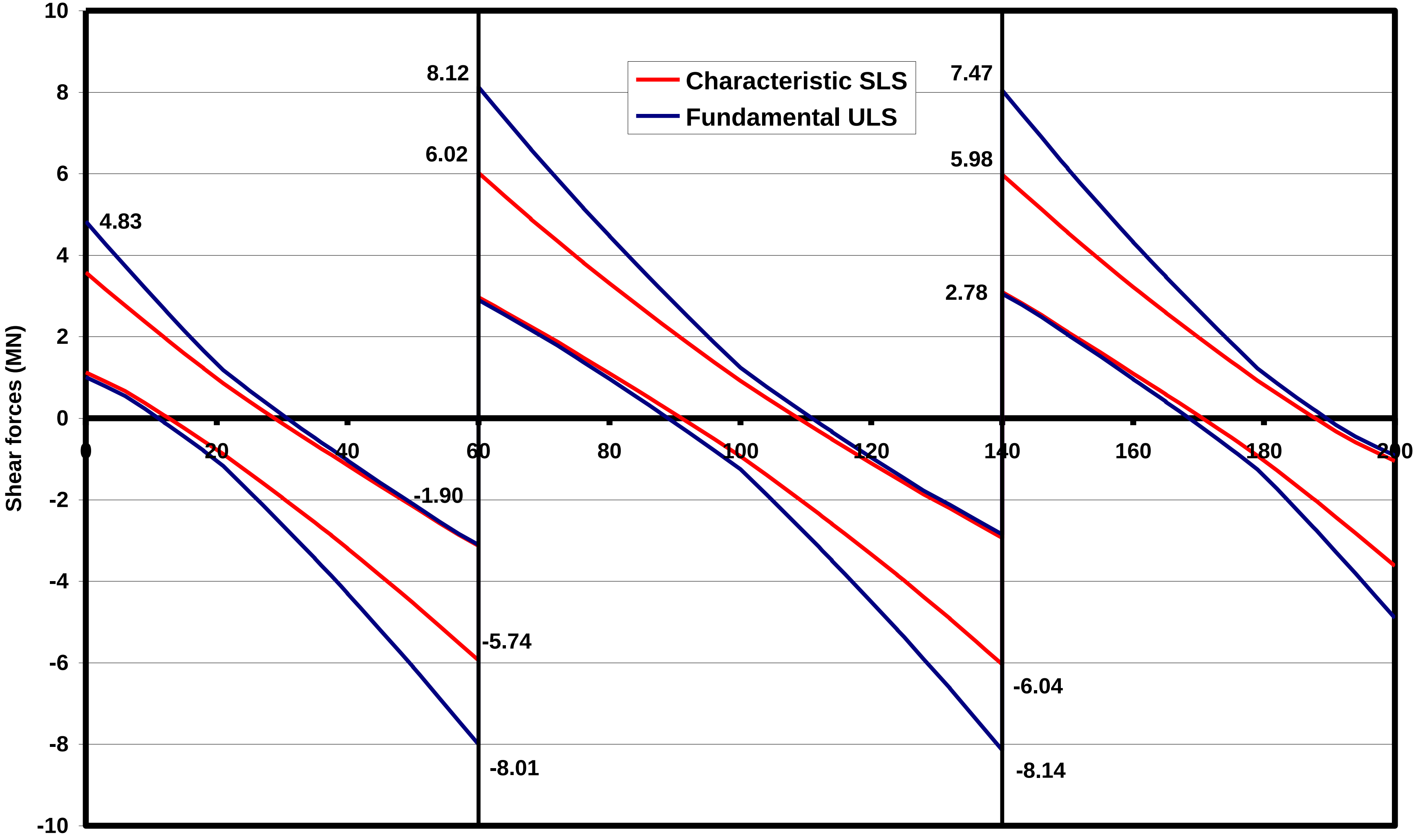
Results for the twin-girder bridge example

SLS and ULS bending moment distribution M_{Ed} (= $M_{a,Ed}$ + $M_{c,Ed}$)



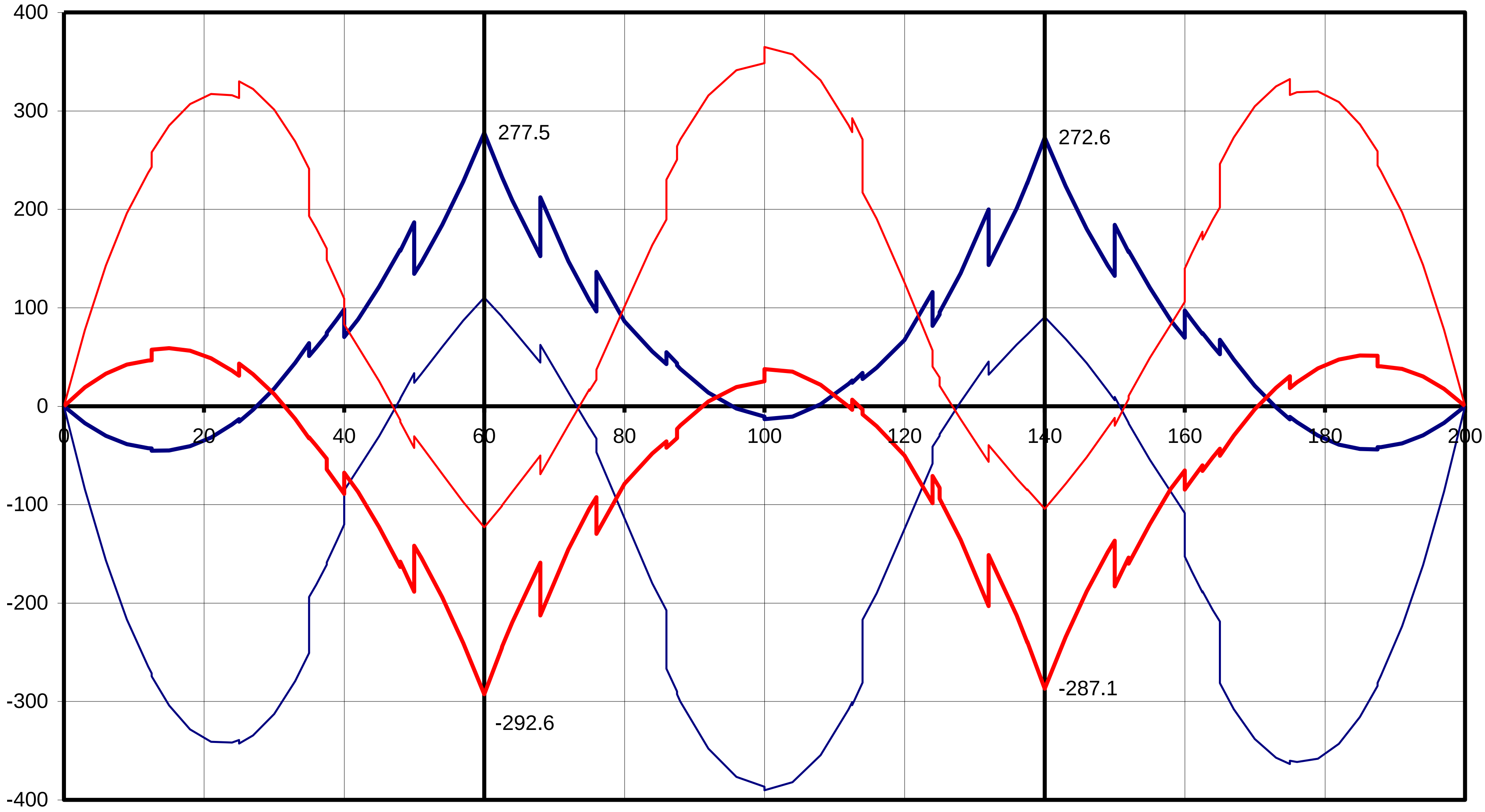
Results for the twin-girder bridge example

SLS and ULS shear force distribution V_{Ed}



Results for the twin-girder bridge example

ULS stresses (N/mm²) along the steel flanges, calculated without concrete resistance



The results from the global analysis will be used for :

- the bridge deck cross-section analysis,
- the abutments and piers check,
- the foundation calculations,
- …

Thank you for your attention !