EUROCODES ON CONCRETE STRUCTURES

Opportunities for scientific and technical co-operation in structural concrete

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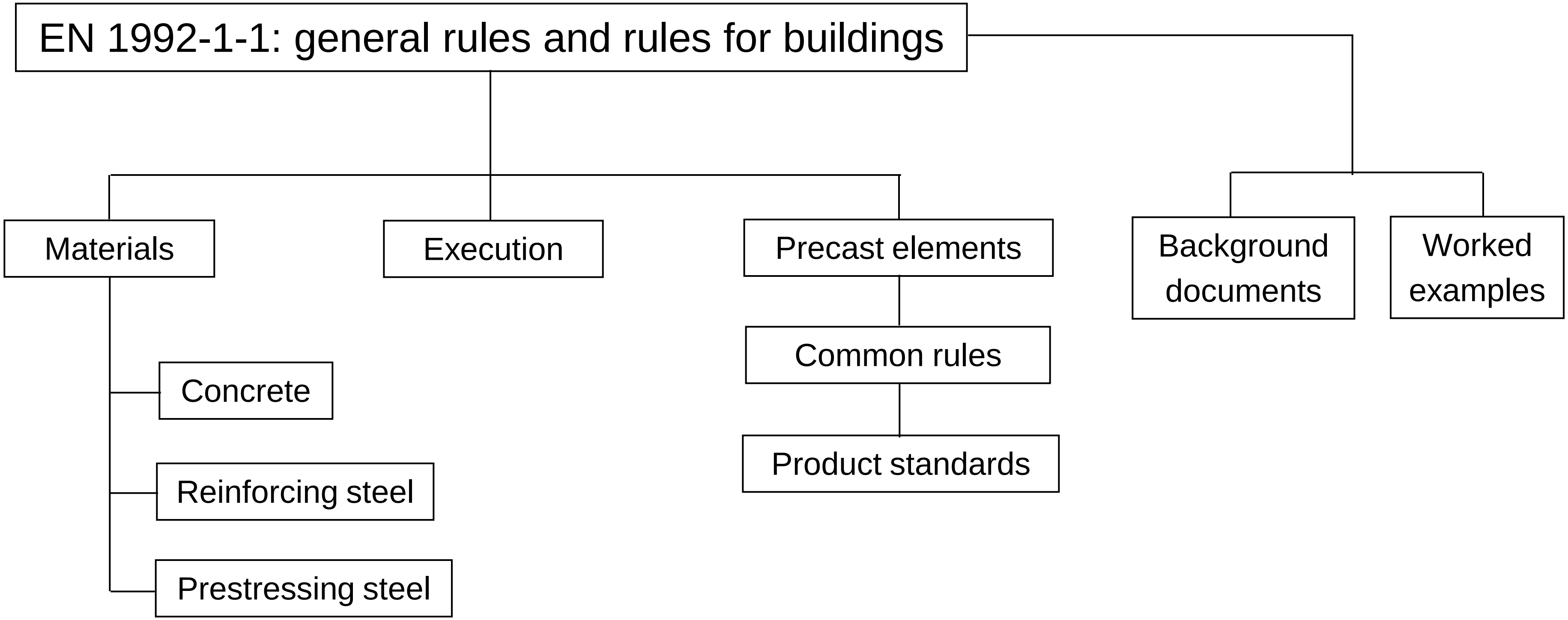
General requirements for a design code

- Scientifically founded
- Consistent and coherent
- Transparent
- Able to recognize new developments
- Open minded: models with different refinement degree allowed
- In harmony with existing codes
- As simple as possible, but not simpler

EN 1992 – Concrete Structures



EN 1992-1-1: general rules and rules for buildings

Materials

Execution

Precast elements

Background documents

Worked examples

Concrete

Reinforcing steel

Prestressing steel

Common rules

Product standards

EN 1992 – Concrete Structures

EN 1992-1-2	*General rules – Structural fire design*
EN 1992-2	*Concrete bridges – Design and detailing rules*
EN 1992-3	*Liquid retaining and containment structures*

EN 1992-1-1 *General Rules and Rules for Buildings*

Content:

1. General
2. Basics
3. Materials
4. Durability and cover
5. Structural analysis
6. Ultimate limit states
7. Serviceability limit states
8. Detailing of reinforcement
9. Detailing of members and particular rules
10. Additional rules for precast concrete elements and structures
11. Lightweight aggregate concrete structures
12. Plain and lightly reinforced concrete structures

EN 1992-1-1 *General Rules and Rules for Buildings*

Annexes:

A. Modifications of safety factor *(I)*
B. Formulas for creep and shrinkage *(I)*
C. Properties of reinforcement *(N)*
D. Prestressing steel relaxation losses *(I)*
E. Indicative strength classes for durability *(I)*
F. In-plane stress conditions *(I)*
G. Soil structure interaction *(I)*
H. Global second order effects in structures *(I)*
I. Analysis of flat slabs and shear walls *(I)*
J. Detailing rules for particular situations *(I)*

I = Informative
N = Normative

EN 1992-1-1 *General Rules and Rules for Buildings*

109 National Determined Parameters

(Suggested Values)

↓

National Choice

Chapter 3: Materials

Concrete strength classes

Concrete strength class C12/15 to C90/105.

(Characteristic cylinder strength / char. cube strength)

Is concrete becoming too strong to test?

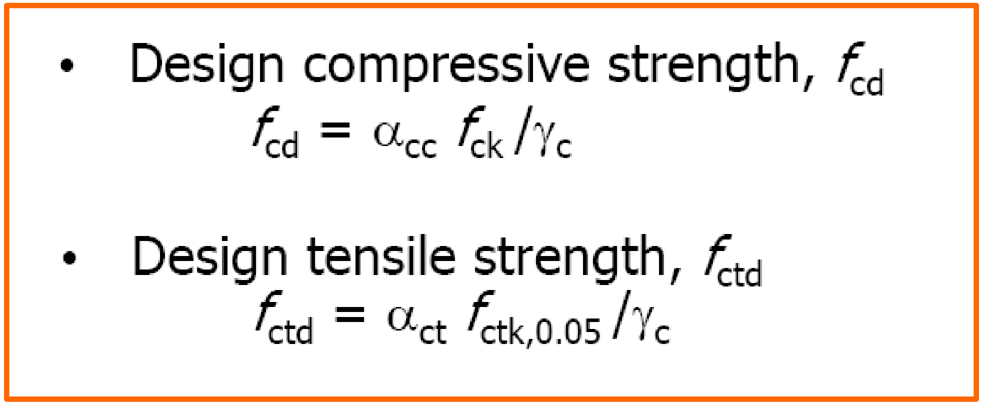
Chapter 3: Materials

Concrete strength classes and properties

	Strength classes for concrete													
f_{ck} (MPa)	12	16	20	25	30	35	40	45	50	55	60	70	80	90
$f_{ck,cube}$ (MPa)	15	20	25	30	37	45	50	55	60	67	75	85	95	105
f_{cm} (MPa)	20	24	28	33	38	43	48	53	58	63	68	78	88	98
f_{ctm} (MPa)	1,6	1,9	2,2	2,6	2,9	3,2	3,5	3,8	4,1	4,2	4,4	4,6	4,8	5,0
$f_{ctk,0,05}$ (MPa)	1 1	1,3	1,5	1,8	2,0	2,2	2,5	2,7	2,9	3,0	3,1	3,2	3,4	3,5
$f_{ctk,0,95}$ (MPa)	2,0	2,5	2,9	3,3	3,8	4,2	4,6	4,9	5,3	5,5	5,7	6,0	6,3	6,6
E_{cm} (Gpa)	27	29	30	31	32	34	35	36	37	38	39	41	42	44
ε_{c1} (‰)	1,8	1,9	2,0	2,1	2,2	2,25	2,3	2,4	2,45	2,5	2,6	2,7	2,8	2,8
ε_{cu1} (‰)	3,5									3,2	3,0	2,8	2,8	2,8
ε_{c2} (‰)	2,0									2,2	2,3	2,4	2,5	2,6
ε_{cu2} (‰)	3,5									3,1	2,9	2,7	2,6	2,6
n	2,0									1,75	1,6	1,45	1,4	1,4
ε_{c3} (‰)	1,75									1,8	1,9	2,0	2,2	2,3
ε_{cu3} (‰)	3,5									3,1	2,9	2,7	2,6	2,6

Chapter 3: Materials

Design strength values (3.1.6)



- Design compressive strength, f_{cd}

$$f_{cd} = \alpha_{cc}\, f_{ck} / \gamma_c$$

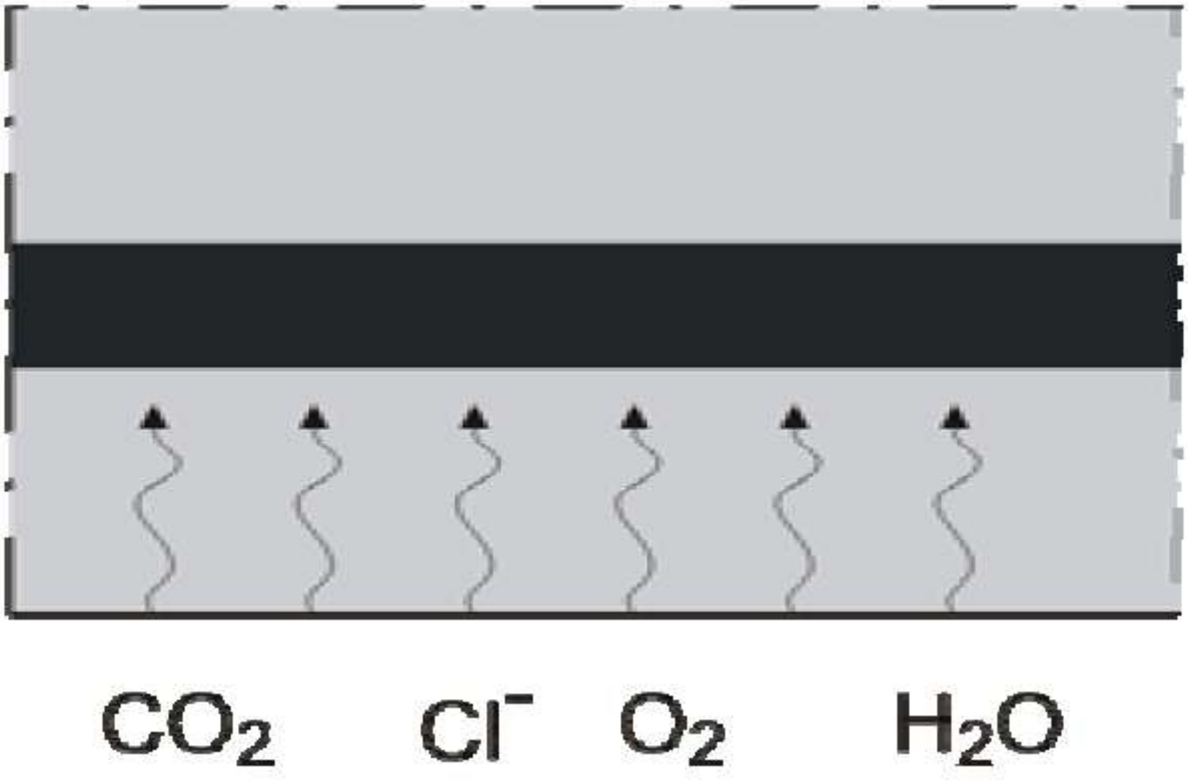
- Design tensile strength, f_{ctd}

$$f_{ctd} = \alpha_{ct}\, f_{ctk,0.05} / \gamma_c$$

α_{cc} (= 1,0) and α_{ct} (= 1,0) are coefficients to take account of long term effects on the compressive and tensile strengths and of unfavourable effects resulting from the way the load is applied (national choice)

Chapter 4: Durability and cover

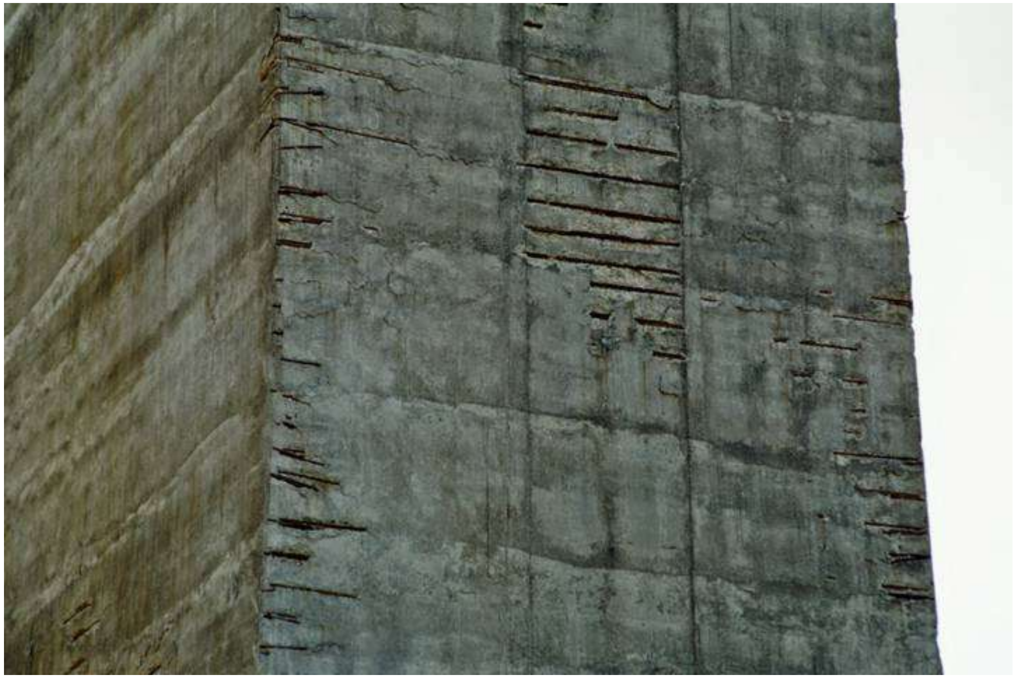
Penetration of corrosion stimulating components in concrete



Chapter 4: Durability and cover

Deterioration of concrete

Corrosion of reinforcement by chloride penetration



Chapter 4: Durability and cover

Avoiding corrosion of steel in concrete

Design criteria

- Aggressivity of environment
- Specified service life

Design measures

- Sufficient cover thickness
- Sufficiently low permeability of concrete (in combination with cover thickness)
- Avoiding harmfull cracks parallel to reinforcing bars

- Other measures like: stainless steel, cathodic protection, coatings, etc.

Chapter 4: Durability and cover

Aggressivity of the environment

Main exposure classes:

The exposure classes are defined in EN206-1. The main classes are:

- XO – no risk of corrosion or attack
- XC – risk of carbonation induced corrosion
- XD – risk of chloride-induced corrosion (other than sea water)
- XS – risk of chloride-induced corrosion (sea water)
- XF – risk of freeze/thaw attack
- XA – chemical attack

Chapter 4: Durability and cover

Procedure to determine $c_{min,dur}$

EN 1992-1-1 leaves the choice of $c_{min,dur}$ to the countries, but gives the following recommendation:

The value $c_{min,dur}$ depends on the “structural class”, which has to be determined first. If the specified service life is 50 years, the structural class is defined as 4. The “structural class” can be modified in case of the following conditions:

-The service life is 100 years instead of 50 years
-The concrete strength is higher than necessary
- Slabs (position of reinforcement not affected by construction process)
- Special quality control measures apply

The final applying service class can be calculated with a table

Chapter 5: Structural Analysis

- **Linear elastic analysis**

1. Suitable for ULS and SLS
2. Assumptions:
   - uncracked cross-sections
   - linear σ - ε relations
   - mean E-modulus
3. Effect of imposed deformations in ULS to be calculated with reduced stiffnesses and creep

Chapter 5: Structural Analysis

- **Linear elastic analysis with limited redistribution**

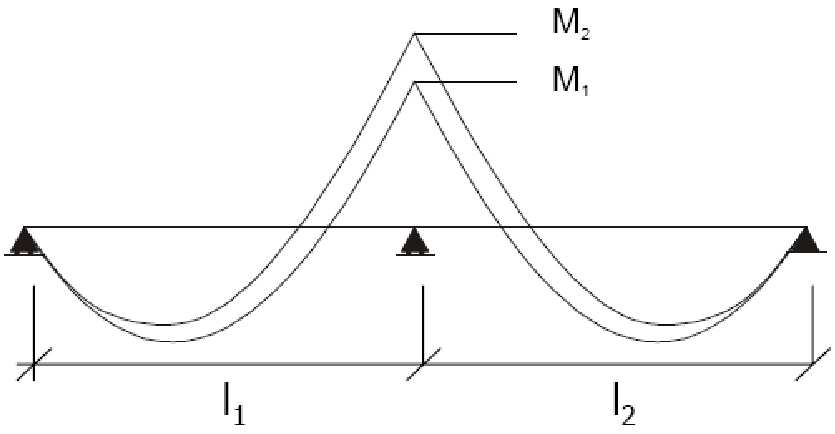
1. Valid for $0,5 \leq l_1 / l_2 \leq 2,0$
2. Ratio of redistribution δ, with

   $\delta \geq k_1 + k_2\, x_u/d$ for $f_{ck} \leq 50$ MPa

   $\delta \geq k_3 + k_4\, x_u/d$ for $f_{ck} > 50$ Mpa

   $\delta \geq k_5$ for reinforcement class B or C

   $\delta \geq k_6$ for reinforcement class A

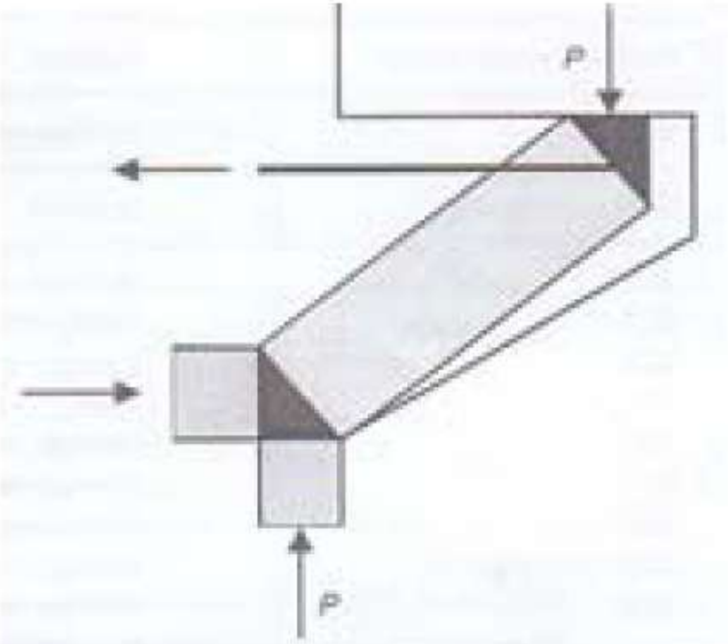


Chapter 5: Structural Analysis

- **Plastic methods of analysis**

Strut and tie analysis (lower bound)

- Suitable for ULS
- Suitable for SLS if compatibility is ensured (direction of struts substantially oriented to compression in elastic analysis)



Chapter 5: Structural Analysis

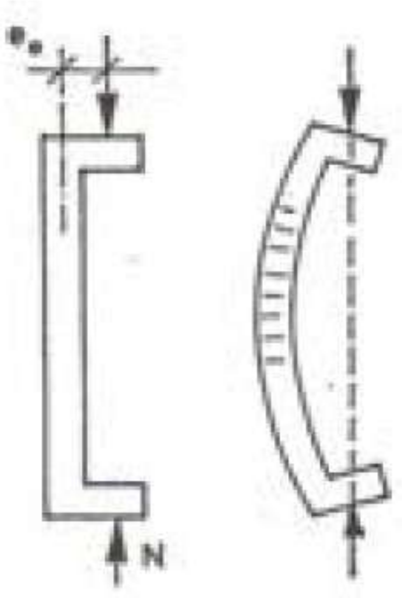
- **Nonlinear analysis**

“Nonlinear analysis may be used for both ULS and SLS, provided that equilibrium and compatibility are satisfied and an adequate nonlinear behaviour for materials is assumed. The analysis may be first or second order”

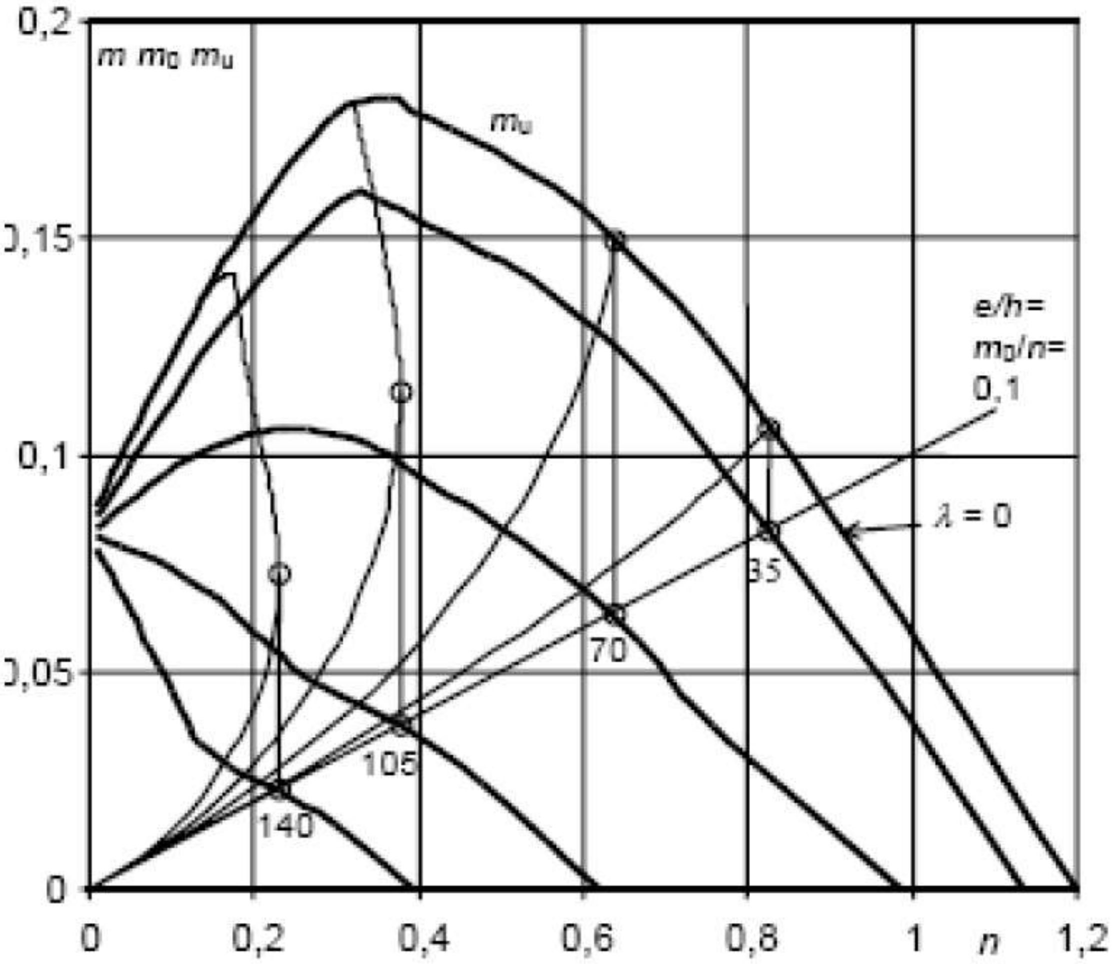
Chapter 5: Structural Analysis

Second order effects with axial loads

- Slenderness criteria for isolated members and buildings (when is 2nd order analysis required?)
- Methods of second order analysis
  - General method based on nonlinear behaviour, including geometric and mechanical nonlinearity
  - Analysis based on nominal stiffness
  - Analysis based on moment magnification factor
  - Analysis based on nominal curvature



Chapter 5: Structural Analysis



Interaction curves for columns of different slenderness, calculated with the general method.

Chapter 5: Structural Analysis

Lateral buckling of beams

No lateral buckling if:

- persistent situations: $\frac{l_{0t}}{b} \leq \frac{50}{(h/b)^{1/3}}$ and $h/b \leq 2{,}5$

- transient situations: $\frac{l_{0t}}{b} \leq \frac{70}{(h/b)^{1/3}}$ and $h/b \leq 3{,}5$

where:

l_{0t} is the distance between torsional restraints
h is the total depth of beam in central part of l_{0t}
b is the width of compression flange

Chapter 6: Ultimate Limit States

Principles of shear control in EN 1992-1-1

Until a certain shear force $V_{Rd,c}$ no calculated shear reinforcement is necessary (only in beams minimum shear reinforcement is prescribed)

If the design shear force is larger than this value $V_{Rd,c}$ shear reinforcement is necessary for the full design shear force. This shear reinforcement is calculated with the variable inclination truss analogy. To this aim the strut inclination may be chosen between two values (recommended range $1 \leq \cot\theta \leq 2{,}5$)

The shear reinforcement may not exceed a defined maximum value to ensure yielding of the shear reinforcement

Chapter 6: Ultimate Limit States

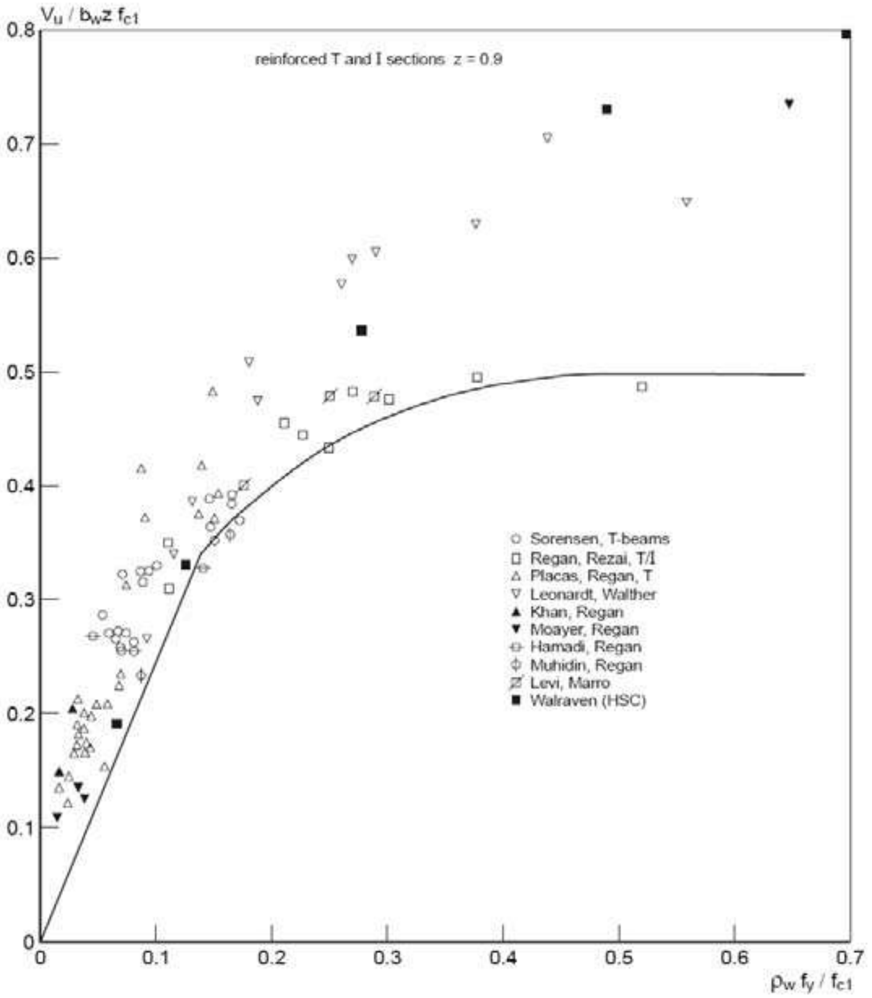
Advantage of variable angle truss analogy

- Freedom of design:
  - Low angle θ leads to low shear reinforcement
  - High angle θ leads to thin webs, saving concrete and dead weight

  Optimum choice depends on type of structure

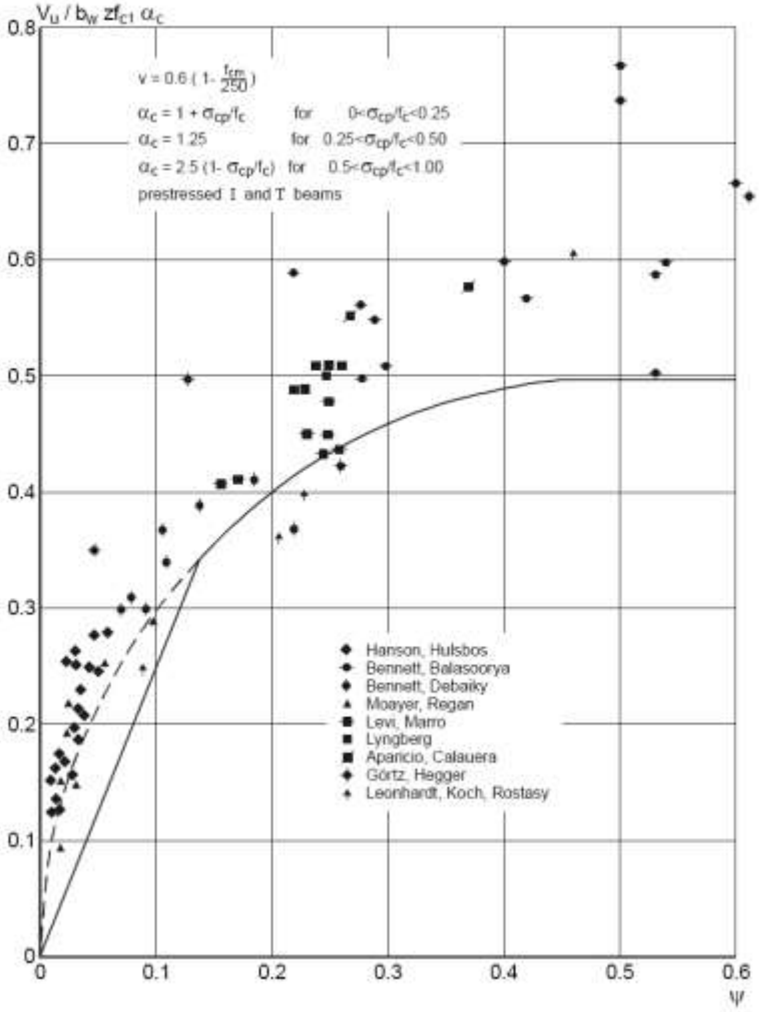
- Transparent equilibrium model, easy in use

Chapter 6: Ultimate Limit States



Non prestressed beams with vertical stirrups – relationship between shear strength and stirrup reinforcement

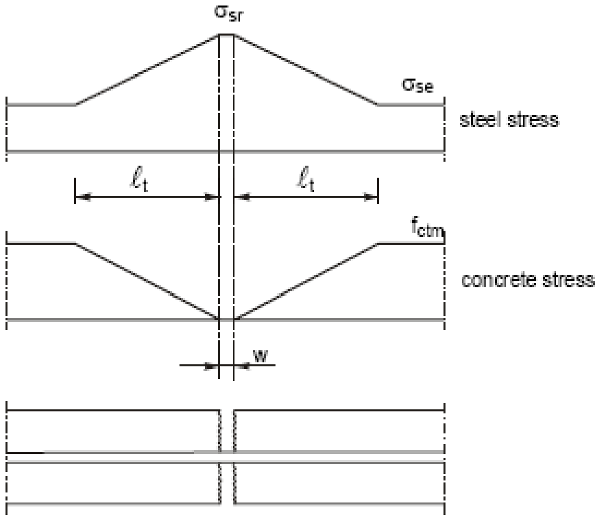
Chapter 6: Ultimate Limit States



Experimental results of shear tests on prestressed beams with shear reinforcement, in comparison with the calculated results according to the variable strut inclination method,

Chapter 7: Serviceability Limit States

EN 1992-1-1 formulae for crack width control



For the calculation of the maximum (or characteristic) crack width, the difference between steel and concrete deformation has to be calculated for the largest crack distance, which is $s_{r,max} = 2l_t$. So

$$w_k = s_{r,max}(\varepsilon_{sm} - \varepsilon_{cm})$$

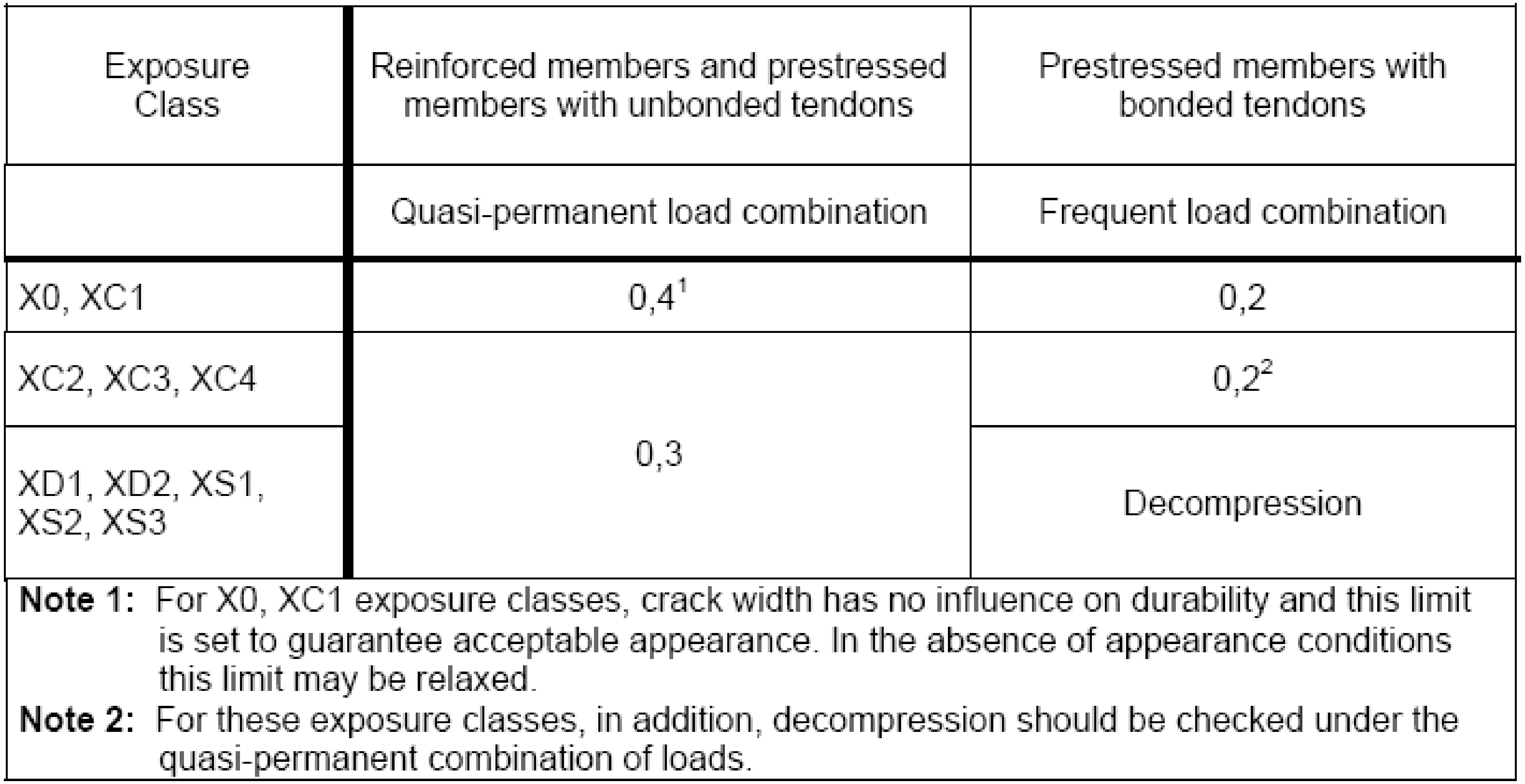
where

$s_{r,max}$	is the maximum crack distance
$(\varepsilon_{sm} - \varepsilon_{cm})$	is the difference in deformation between steel and concrete over the maximum crack distance.

Accurate formulations for $s_{r,max}$ and $(\varepsilon_{sm} - \varepsilon_{cm})$ are given

Chapter 7: Serviceability Limit States

EN 1992-1-1 requirements for crack width control (recommended vales)

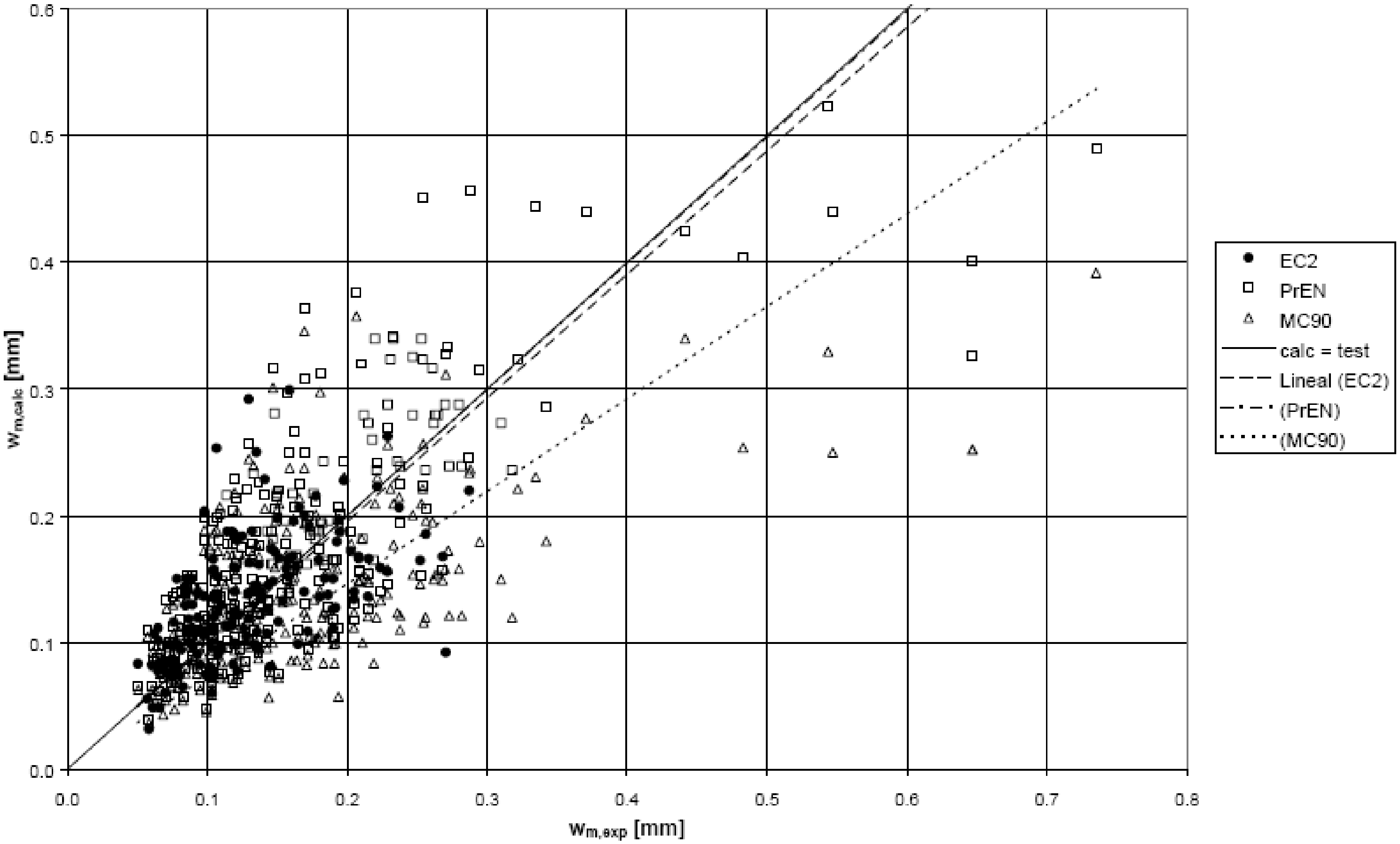


Exposure Class	Reinforced members and prestressed members with unbonded tendons	Prestressed members with bonded tendons
	Quasi-permanent load combination	Frequent load combination
X0, XC1	0,4[1]	0,2
XC2, XC3, XC4	0,3	0,2[2]
XD1, XD2, XS1, XS2, XS3		Decompression

Note 1: For X0, XC1 exposure classes, crack width has no influence on durability and this limit is set to guarantee acceptable appearance. In the absence of appearance conditions this limit may be relaxed.

Note 2: For these exposure classes, in addition, decompression should be checked under the quasi-permanent combination of loads.

Chapter 7: Serviceability Limit States



Comparison test-calc., acc. to EC2, MC90 and PrEN

Chapter 7: Serviceability Limit States

Calculating the deflection of a concrete member

The deflection follows from: $\delta = \zeta\, \delta_{II} + (1 - \zeta)\, \delta_I$

δ deflection
δ_I deflection fully cracked
δ_{II} deflection uncracked
ζ coefficient for tension stiffening (transition coefficient)

$\zeta = 1 - \beta\, (\sigma_{sr}/\sigma_s)^2$

σ_{sr} steel stress at first cracking
σ_s steel stress at quasi permanent service load
β 1,0 for single short-term loading
0,5 for sustained loads or repeated loading

Chapter 8: Detailing of reinforcement

Design anchorage lengt l_{bd}

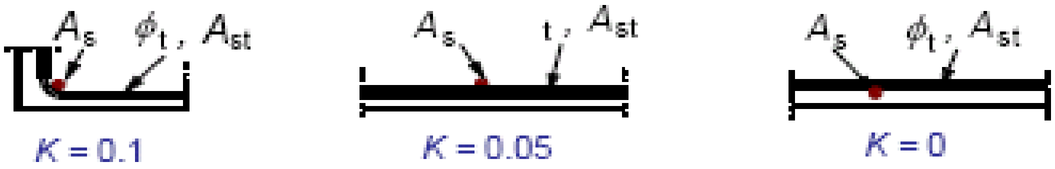
$$\boldsymbol{l_{bd} = \alpha_1 \alpha_2 \alpha_3 \alpha_4 \alpha_5 l_{b,rqd} \geq l_{b,min}}$$

α_1 effect of bends — For straight bars α_1 = 1.0, otherwise 0.7

α_2 effect of concrete cover — $\alpha_2 = 1 - 0.15(\text{cover} - \varphi)/\varphi \geq 0.7$ and ≤ 1.0

α_3 effect of confinement by transverse reinforcement (not welded)

$\alpha_3 = 1 - K\lambda \geq 0.7$ and ≤ 1.0 where $\lambda = (\Sigma A_{st} - \Sigma A_{st,min})/A_s$



α_4 effect of confinement by welded transverse reinforcement $\alpha_4 = 0.7$

α_5 effect of confinement by transverse pressure

$\alpha_5 = 1 - 0.04p \geq 0.7$ and ≤ 1.0

where p is the transverse pressure (MPa) at ULS along l_{bd}

$(\alpha_2, \alpha_3, \alpha_5) \geq 0.7$ **$l_{b,min} > \max(0.3 l_b; 15\varphi, 100\text{mm})$**

EN 1992-2 Concrete Bridges

- Linear elastic analysis with limited redistributions

Limitation of δ due to uncertaintes on size effect
and bending-shear interaction

$\delta \geq 0.85$ (recommended value)

- Plastic analysis

Restrictions due to uncertaintes on size effect and bending-shear interaction:

$$\frac{x_u}{d} \leq \begin{cases} 0.15 \text{ for concrete strength classes } \leq \text{ C50/60} \\ 0.10 \text{ for concrete strength classes } \geq \text{ C55/67} \end{cases}$$

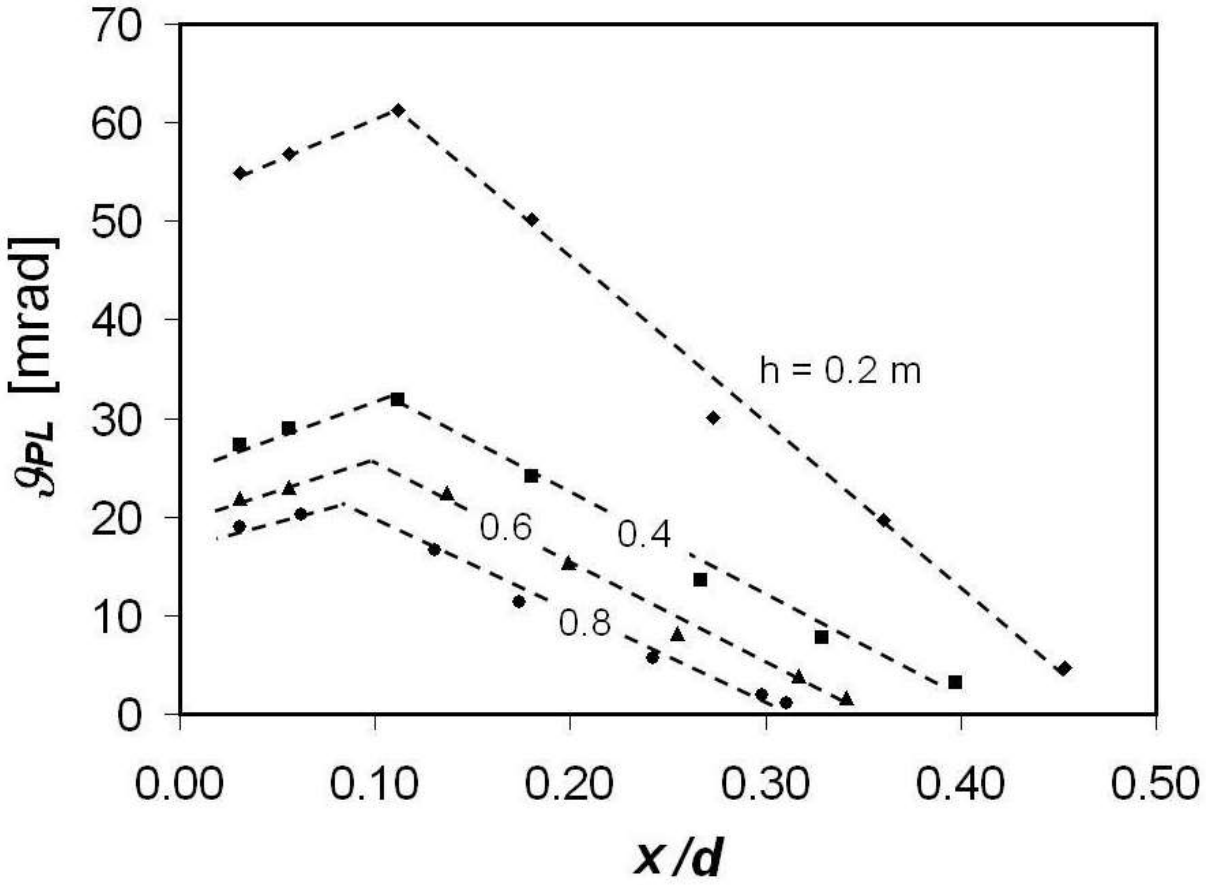
- Rotation capacity

Restrictions due to uncertaintes on size effect and bending-shear interaction:

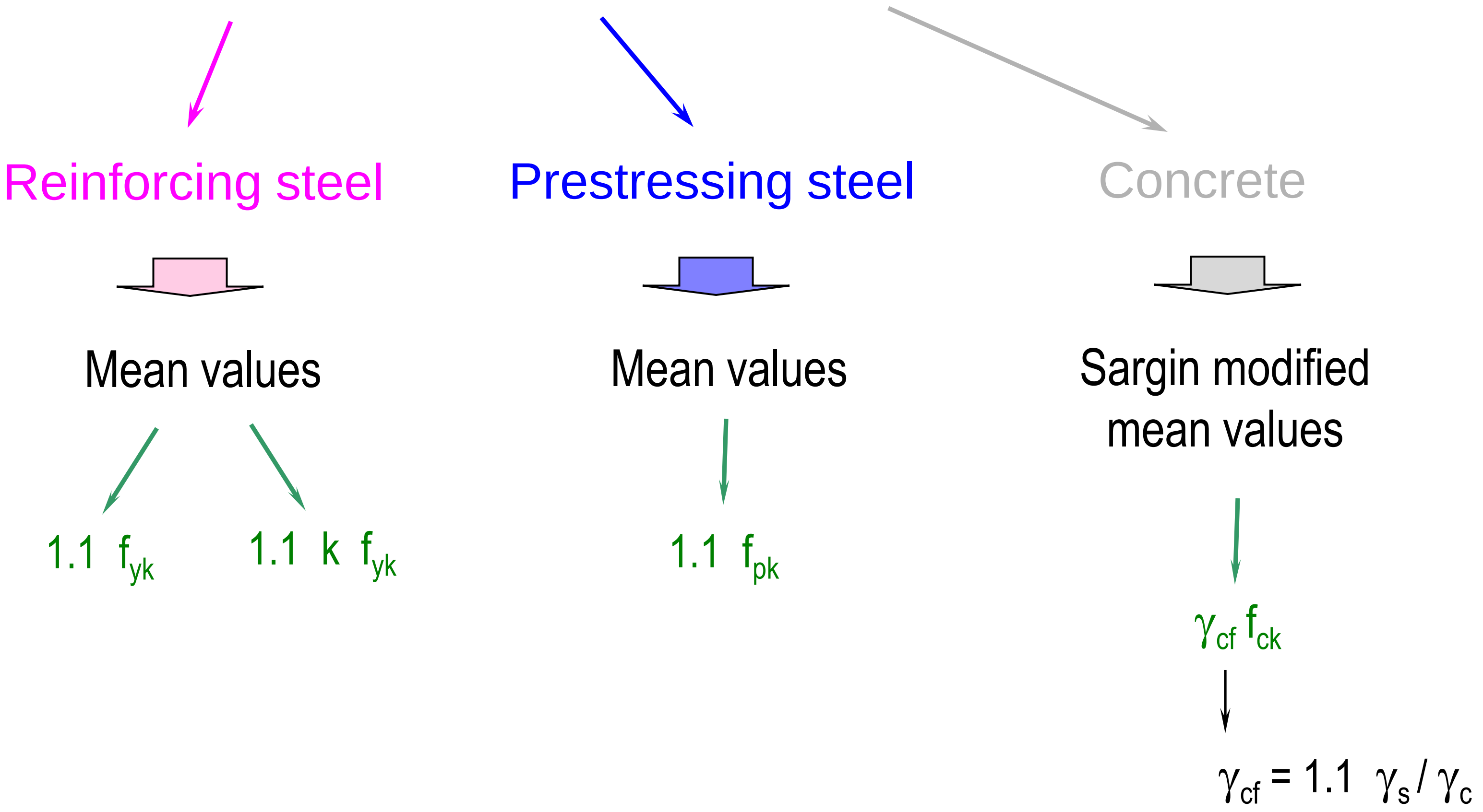
in plastic hinges

$$\frac{x_u}{d} \leq \begin{cases} 0.30 \text{ for concrete strength classes } \leq \text{ C50/60} \\ 0.23 \text{ for concrete strength classes } \geq \text{ C55/67} \end{cases}$$

Numerical rotation capacity



- Nonlinear analysis ⇒ Safety format



Reinforcing steel

Mean values

$1.1\ f_{yk}$

$1.1\ k\ f_{yk}$

Prestressing steel

Mean values

$1.1\ f_{pk}$

Concrete

Sargin modified
mean values

$\gamma_{cf}\ f_{ck}$

$\gamma_{cf} = 1.1\ \gamma_s / \gamma_c$

Design format

- Incremental analysis from SLS, so to reach $\gamma_G G_k + \gamma_Q Q$ in the same step
- Continuation of incremental procedure up to the peak strength of the structure, in corrispondance of ultimate load q_{ud}
- Evaluation of structural strength by use of a global safety factor γ_0

$$R\left(\frac{q_{ud}}{\gamma_0}\right)$$

- Verification of one of the following inequalities

$$\gamma_{Rd} E\left(\gamma_G G + \gamma_Q Q\right) \le R\left(\frac{q_{ud}}{\gamma_O}\right)$$

$$E\left(\gamma_G G + \gamma_Q Q\right) \le R\left(\frac{q_{ud}}{\gamma_{Rd} \cdot \gamma_O}\right)$$

(i.e.) $R\left(\frac{q_{ud}}{\gamma_{O'}}\right)$

$$\gamma_{Rd} \gamma_{Sd} E\left(\gamma_g G + \gamma_q Q\right) \le R\left(\frac{q_{ud}}{\gamma_O}\right)$$

With

$$\begin{cases} \gamma_{Rd} = 1.06 \text{ partial factor for model uncertainties (resistence side)} \\ \gamma_{Sd} = 1.15 \text{ partial factor for model uncertainties (actions side)} \\ \gamma_{0} = 1.20 \text{ structural safety factor} \end{cases}$$

If $\gamma_{Rd} = 1.00$ then $\gamma_{0'} = 1.27$ is the structural safety factor

Section 6 ⇒ Ultimate limit state (ULS)

- Robustness criteria for prestressed structures

3 different approaches

a) Verification of load capacity with a reduced area of prestressing

- Evaluation of bending moment in frequent combination of actions: M_{freq}
- Reduction of prestressing up the reaching of f_{ctm} at the extreme tensed fibre, in presence of M_{freq}
- Evaluation of resisting bending moment M_{Rd} with reduced prestressing and check that:

$$M_{Rd} > M_{freq}$$

Redistributions can be applied

Material partial safety factors as for accidental combinations

b) Verification with nil residual prestressing

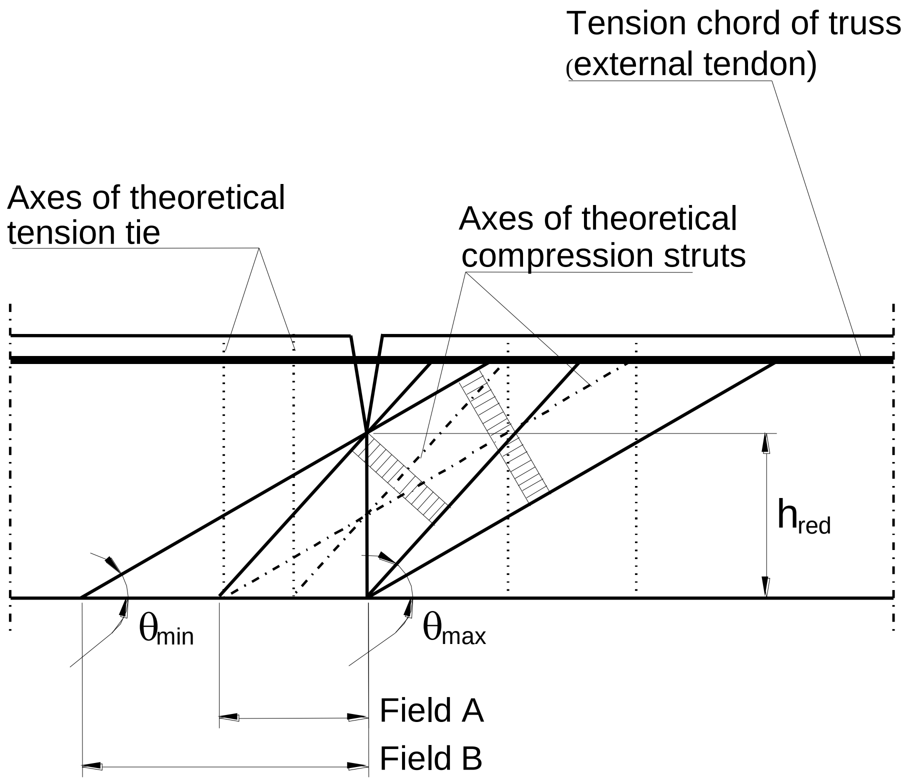
- Provide a minimum reinforcement so that

$$A_{s,\min} = \frac{M_{rep}}{z_s \; f_{yk}} \left(- \frac{A_p \cdot \Delta\sigma_p}{f_{yk}} \right) \rightarrow \Delta\sigma_p < 0.4\, f_{ptk} \text{ and } 500\text{ MPa}$$

where M_{rep} is the cracking bending moment evaluated with f_{ctx} (f_{ctm} recommended)

c) Estabilish an appropriate inspection regime (External tendons!)

- Bending–shear behaviour of segmental precast bridges with external prestressing (only)



$$h_{red} = \frac{V_{Ed}}{b_w \, \nu \; f_{cd}} (\cot\theta + \tan\theta)$$

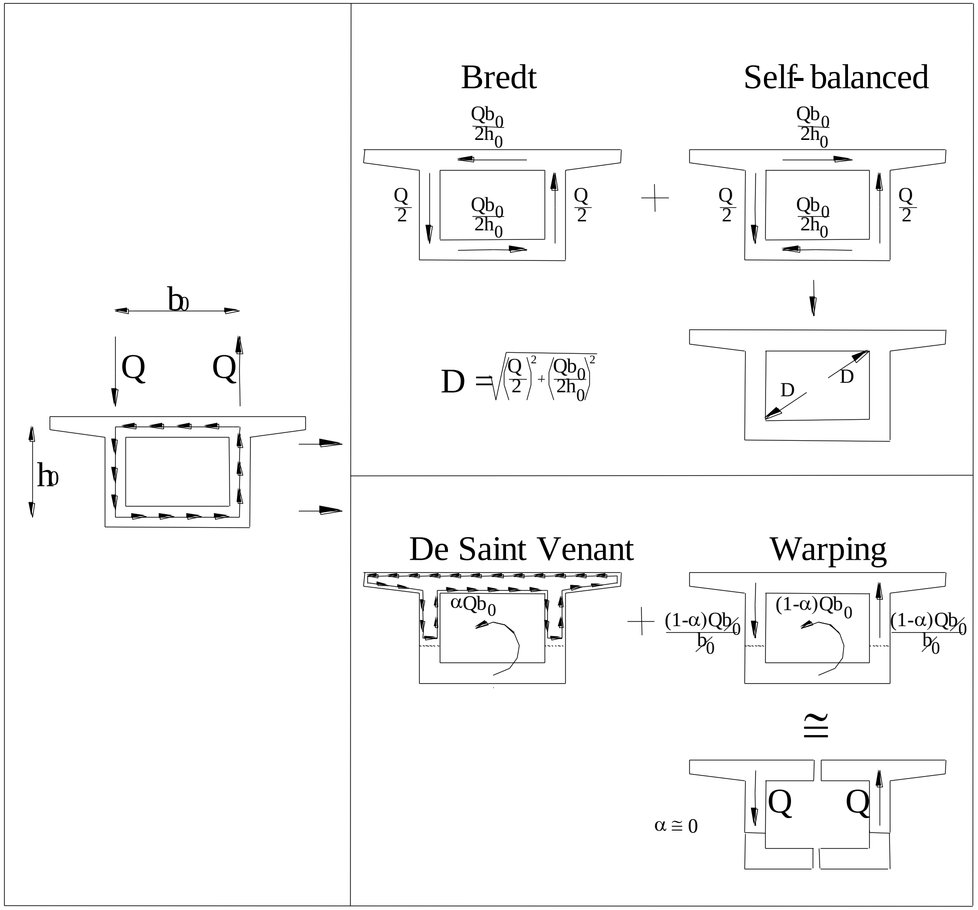
$$\frac{A_{sw}}{s} = \frac{V_{Ed}}{h_{red} \, f_{ywd} \, \cot\theta}$$

$h_{red,min} = 0.5$ h
(recommended value)

Field A : arrangement of stirrups with θ_{max} (cot θ = 1.0)

Field B : arrangement of stirrups with θ_{min} (cot θ = 2.5)

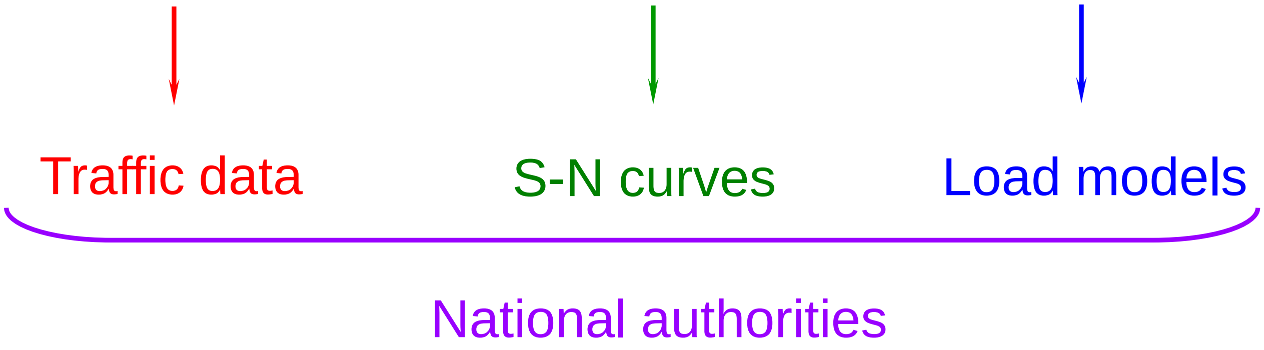
- Bending–shear-torsion behaviour of segmental precast bridges with external prestressing (only)



Design the shear keys so that circulatory torsion can be maintained !

- Fatigue

- Verification of concrete under compression or shear



Traffic data S-N curves Load models

National authorities

- λ values semplified approach (Annex NN, from ENV 1992-2)

Application of Miner rule

$$\sum_{i=1}^{m} \frac{n_i}{N_i} \leq 1$$

$N_i \Rightarrow$

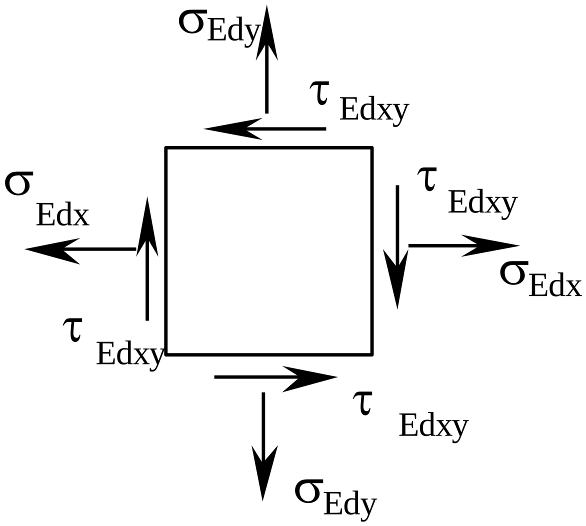
- Given by national authorities (S-N curves)
- $N_i = 10 \exp\left(14 \cdot \frac{1 - E_{cd,\max,i}}{\sqrt{1 - R_i}}\right)$

where: $R_i = \frac{E_{cd,\min,i}}{E_{cd,\max,i}}$; $E_{cd,\min,i} = \frac{\sigma_{cd,\min,i}}{f_{cd,\ fat}}$; $E_{cd,\max,i} = \frac{\sigma_{cd,\max,i}}{f_{cd,\ fat}}$

$$f_{\mathrm{cd,fat}} = k_1 \beta_{\mathrm{cc}}(t_0) f_{\mathrm{cd}} \left(1 - \frac{f_{\mathrm{ck}}}{250}\right)$$

K_1 =0.85 (Recommended value)

- Membrane elements



- Compressive stress field strength defined as a function of principal stresses
- If both principal stresses are compressive

$$\sigma_{cd\,\max} = 0.85\, f_{cd} \frac{1+3{,}80\alpha}{(1+\alpha)^2}$$

is the ratio between the two principal stresses (α ≤ 1)

- Where a plastic analysis has been carried out with $\theta = \theta_{el}$ and at least one principal stress is in tension and no reinforcement yields

$$\sigma_{cd\,\max} = f_{cd}\left[0,85 - \frac{\sigma_s}{f_{yd}}\left(0,85-\nu\right)\right]$$

is the maximum tensile stress value in the reinforcement

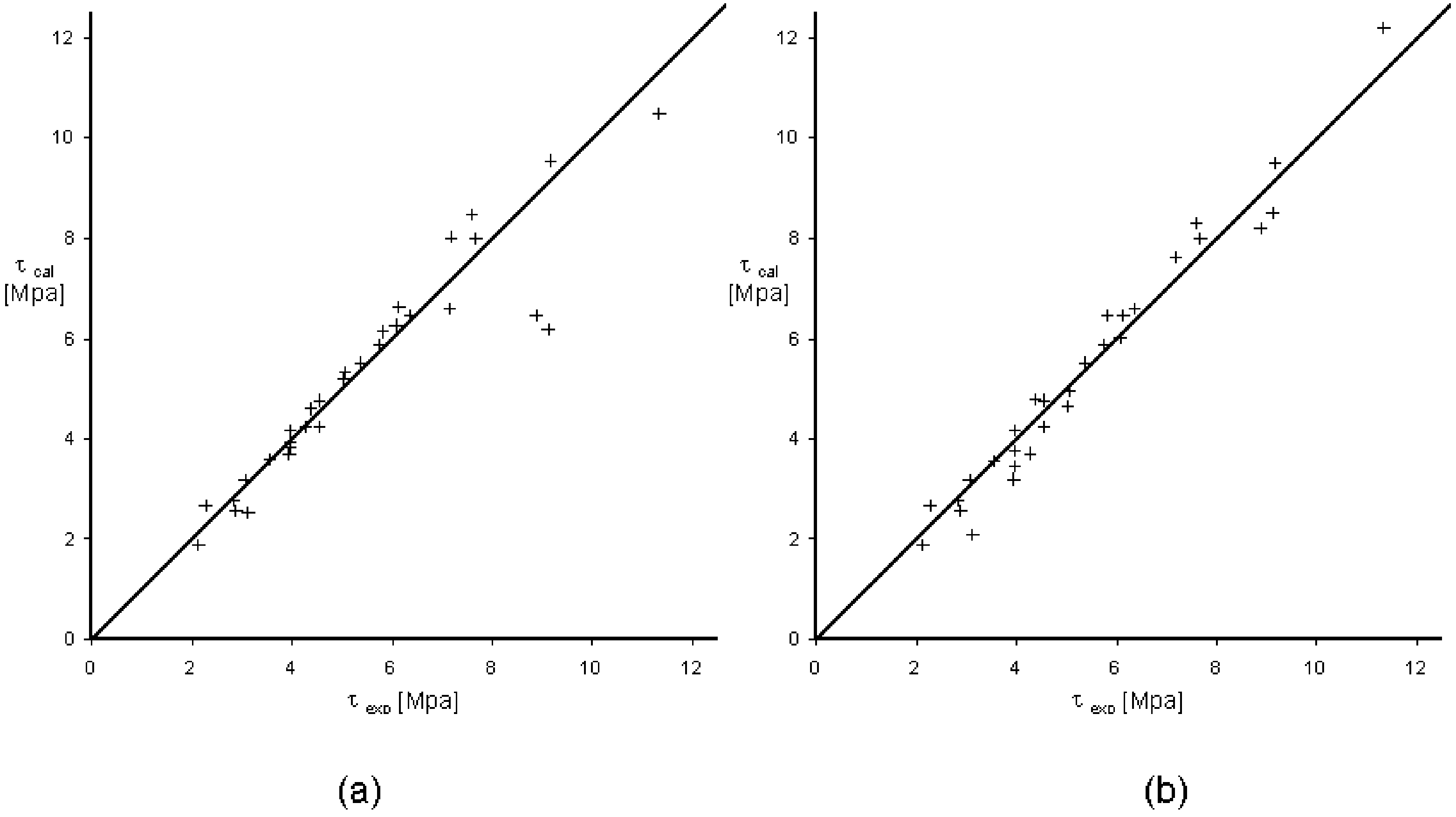
- Where a plastic analysis is carried out with yielding of any reinforcement

$$\sigma_{cd\,\max} = \nu\; f_{cd}\left(1-0,032\left|\theta-\theta_{el}\right|\right)$$

is the angle to the X axis of plastic compression field at ULS (principal compressive stress)

$\left|\theta-\theta_{el}\right| \leq 15$ degrees

is the inclination to the X axis of principal compressive stress in the elastic analysis



Experimental versus calculated panel strenght by Marti and Kaufmann (a) and by Carbone, Giordano and Mancini (b)

Section 8 ⇒ Detailing of reinforcement and prestressing tendons

- Couplers for prestressing tendons
- In the same section maximum 67% of coupled tendons
- For more than 50% of coupled tendons:

Continous minimum reinforcement

or

Residual stress > 3 MPa in characteristic combination

- Minimum distance of sections in which couplers are used

Construction depth h	Distance a
≤ 1,5 m	1,5 m
1,5 m < h < 3,0 m	a = h
≥ 3,0 m	3,0 m

- For tendons anchored at a construction joint a minimum residual compressive stress of 3 MPa is required under the frequent combination of actions, otherwise reinforcement should be provided to carter for the local tension behind the anchor

Annex KK ⇒ Structural effects of time dependent behaviour of concrete

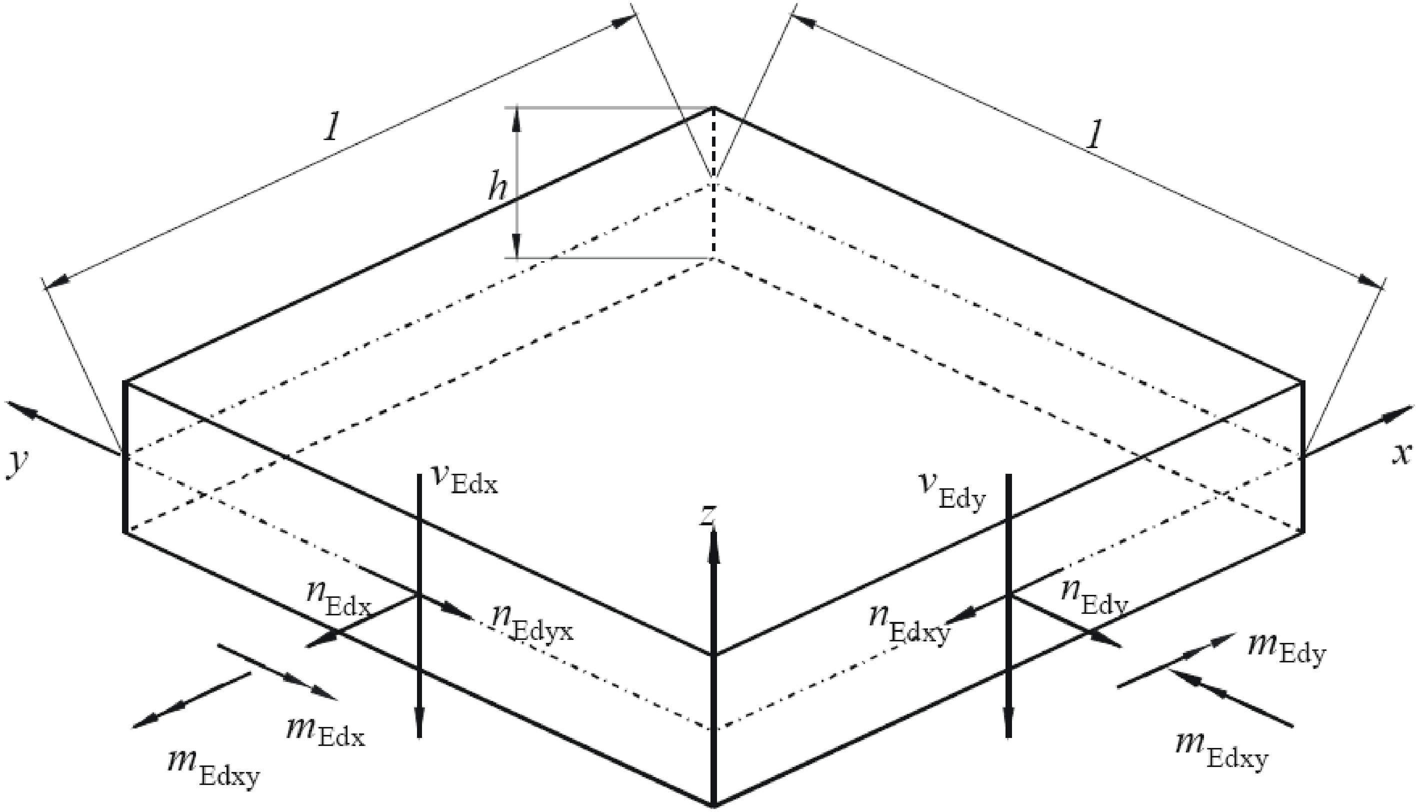
Assumptions

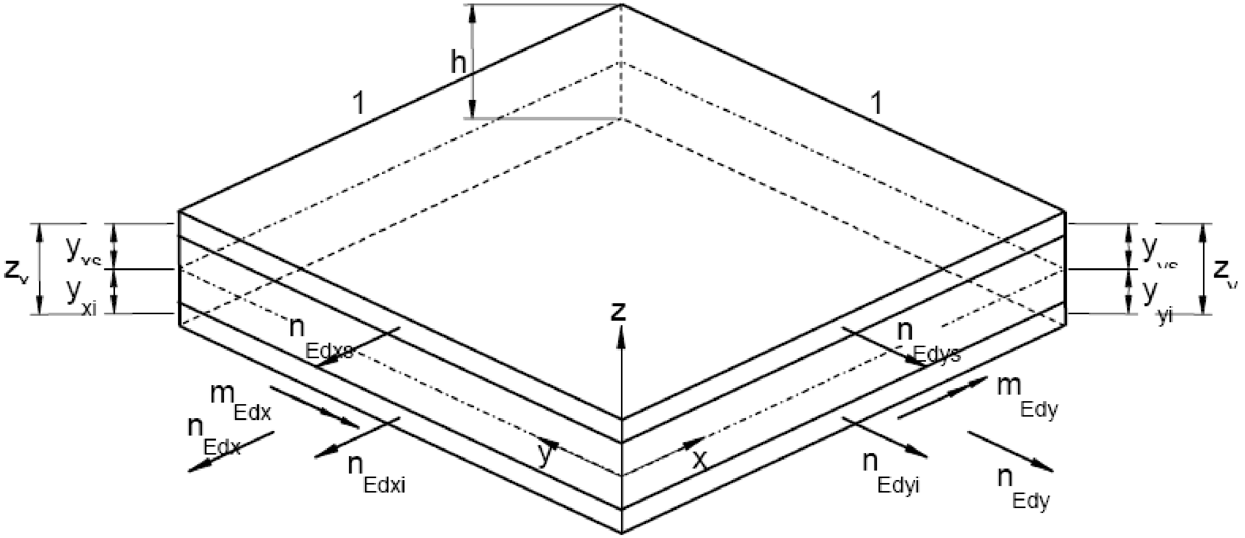
- *Creep and shrinkage indipendent of each other*
- *Average values for creep and shrinkage within the section*
- *Validity of principle of superposition (Mc-Henry)*

Type of analysis	Comment and typical application
General and incremental step-by-step method	These are general methods and are applicable to all structures. Particularly useful for verification at intermediate stages of construction in structures in which properties vary along the length (e.g.) cantilever construction.
Methods based on the theorems of linear viscoelasticity	Applicable to homogeneous structures with rigid restraints.
The ageing coefficient method	This mehod will be useful when only the long-term distribution of forces and stresses are required. Applicable to bridges with composite sections (precast beams and in-situ concrete slabs).
Simplified ageing coefficient method	Applicable to structures that undergo changes in support conditions (e.g.) span-to- span or free cantilever construction.

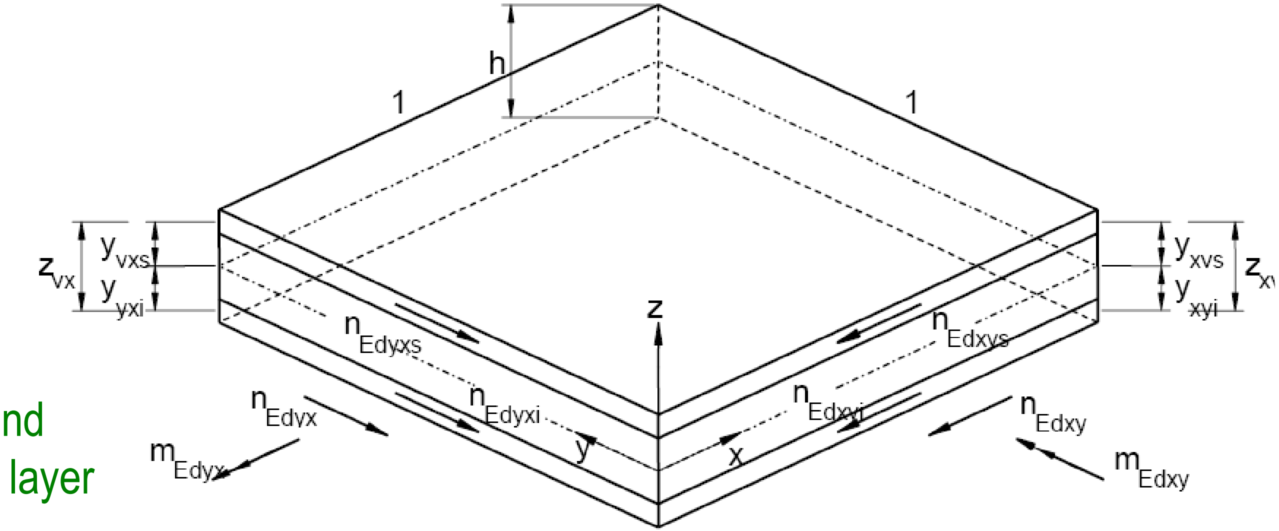
Annex LL ⇒ Concrete shell elements

A powerfull tool to design 2D elements





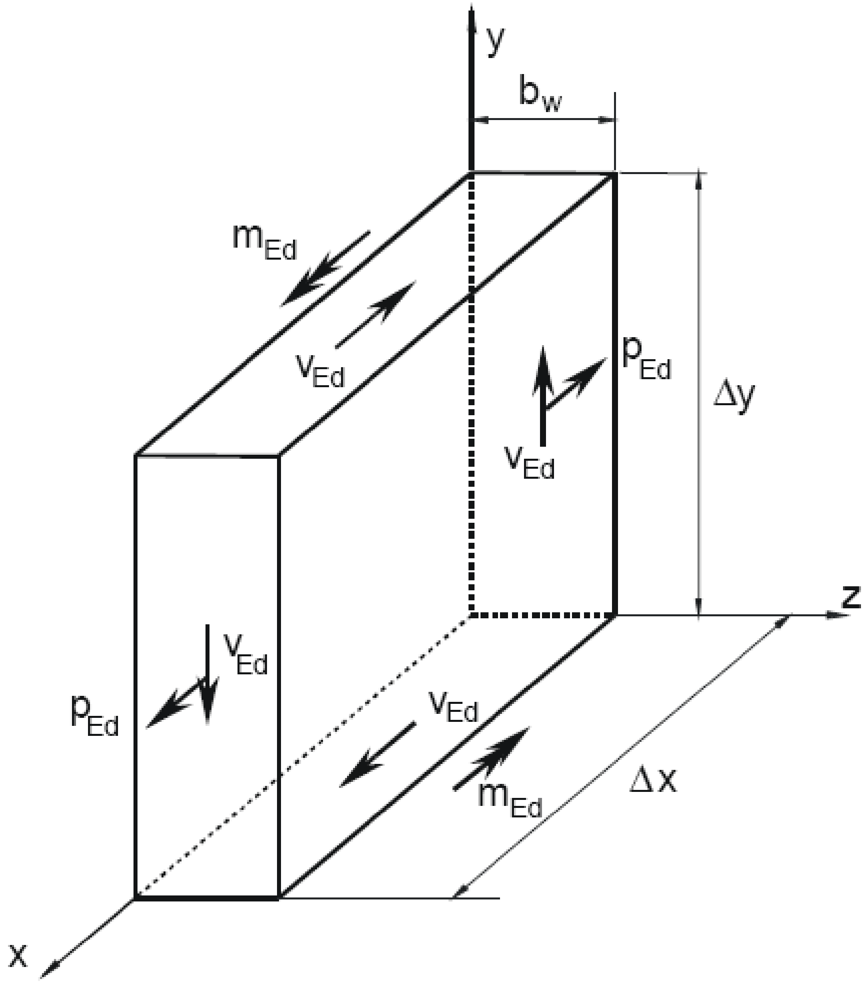
Axial actions and bending moments in the outer layer

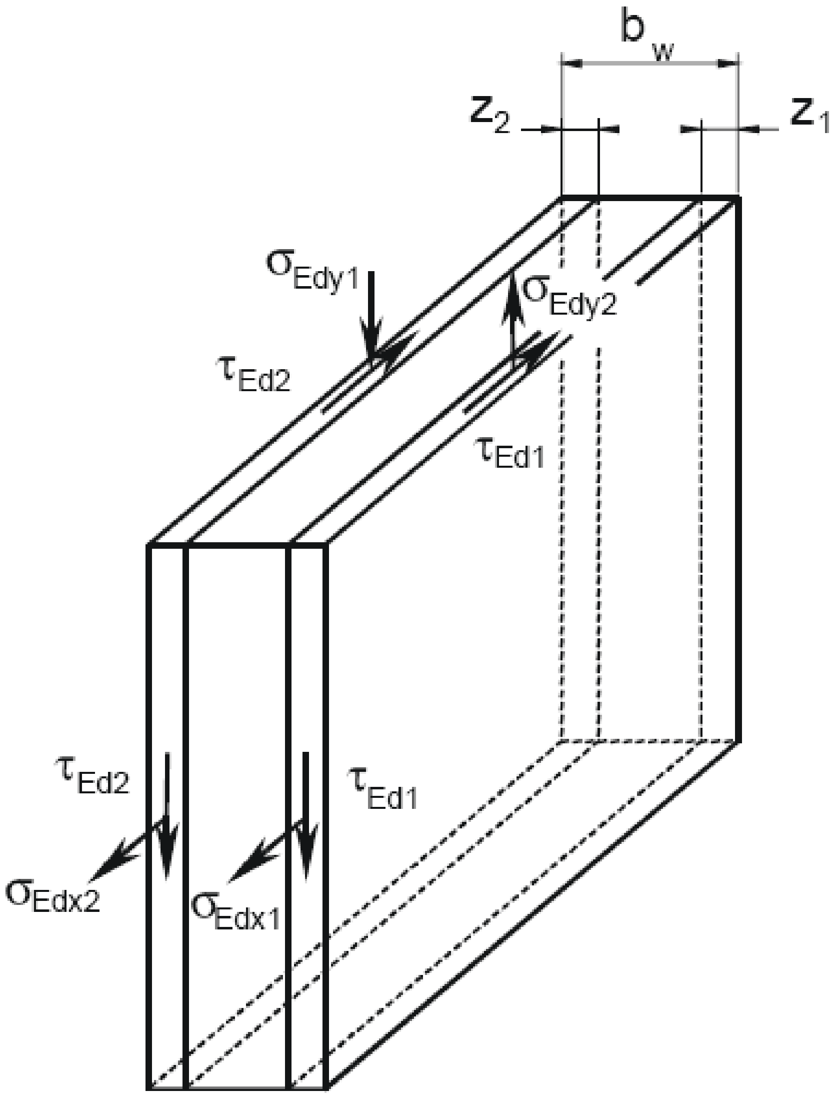


Membrane shear actions and twisting moments in the outer layer

Annex MM ⇒ Shear and transverse bending

Webs of box girder bridges





Modified sandwich model

EN 1992 – i

A complete set of codes for sustainable design of concrete structures