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Eurocode requirements for concrete design

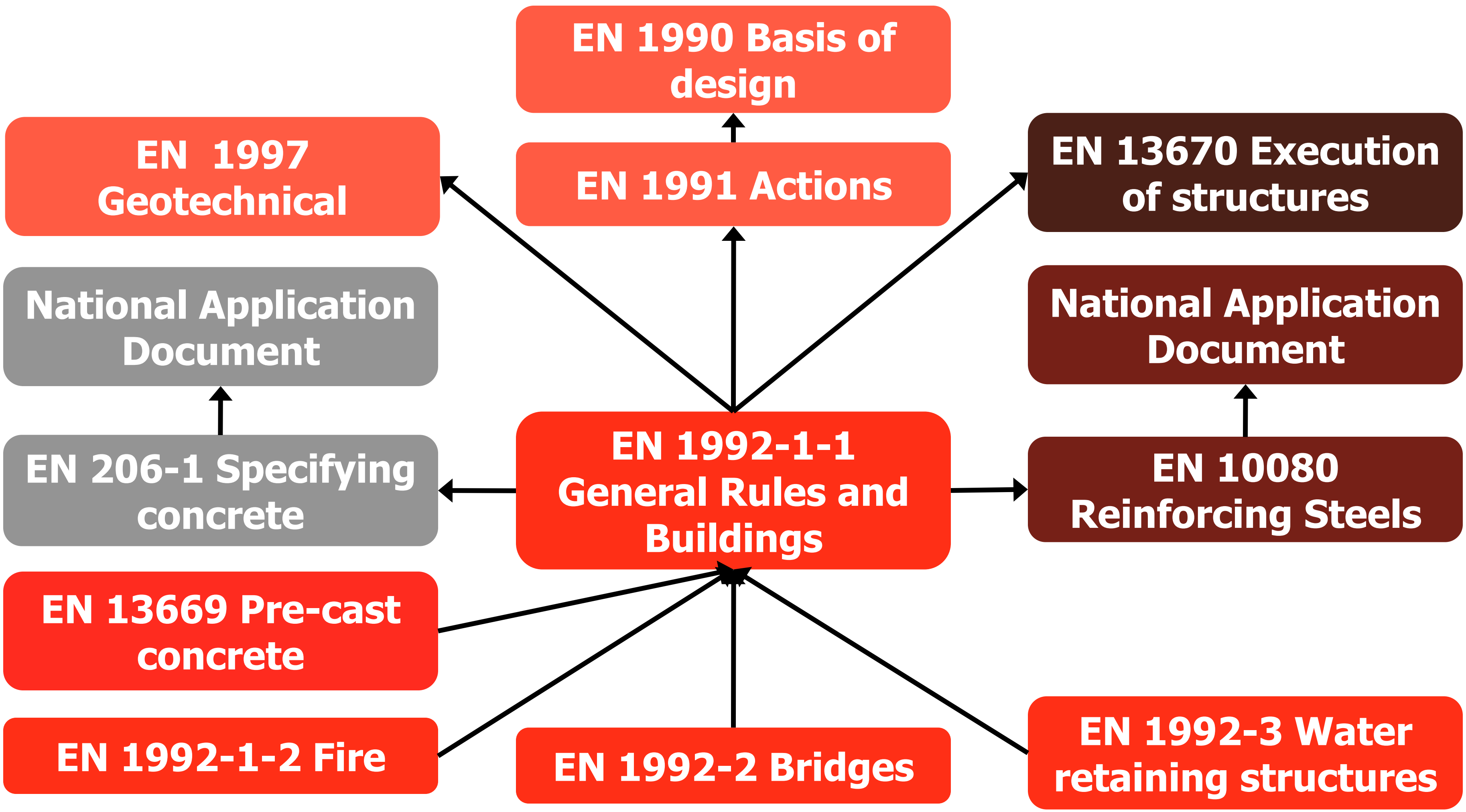
Dr Stephen Hicks

Overview of presentation

- Introduction to Eurocode 2
- Materials, durability and structural analysis
- Flexural design
- Shear design
- Axial resistance
- Serviceability limit state

Introduction to Eurocode 2

Eurocode 2 relationships



Eurocode 2 - Contents

1. General
2. Basis of design
3. Materials
4. Durability and cover to reinforcement
5. Structural analysis
6. Ultimate limit state
7. Serviceability limit state
8. Detailing of reinforcement and pre-stressing tendons – General
9. Detailing of member and particular rules
10. Additional rules for precast concrete elements and structures
11. Lightweight aggregated concrete structures
12. Plain and lightly reinforced concrete structures

Eurocode 2 - Annexes

A. **(Informative)** Modification of partial factors for materials
B. **(Informative)** Creep and shrinkage strain
C. **(Normative)** Reinforcement properties
D. **(Informative)** Detailed calculation method for pre-stressing steel relaxation losses
E. **(Informative)** Indicative Strength Classes for durability
F. **(Informative)** Reinforcement expressions for in-plane stress conditions
G. **(Informative)** Soil structure interaction
H. **(Informative)** Global second order effects in structures
I. **(Informative)** Analysis of flat slabs and shear walls
J. **(Informative)** Examples of regions with discontinuity in geometry or action (Detailing rules for particular situations)

Materials, durability and structural analysis

Materials, durability and structural analysis

MATERIALS - CONCRETE

Concrete - Introduction

- Density assumed to be 25kN/m^3 for concrete with normal percentage of reinforcing steel (EN 1991-1-1)

- Designs are based on cylinder strength, f_{ck}

- Strength classes are defined as Cx/y, where x and y are the 28-day cylinder and cube strength, respectively (for lightweight aggregate, density between 10 to 21 kN/m^3 and the strength classes become LCx/y)

- Maximum value of characteristic strength
- C90/105 for buildings
- C70/85 for bridges

Concrete 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
E_{cm} (GPa)	27	29	30	31	33	34	35	36	37	38	39	41	42	44

f_{ck} = Concrete cylinder strength

$f_{ck,cube}$ = Concrete cube strength

f_{cm} = Mean concrete strength

f_{ctm} = Mean concrete tensile strength

E_{cm} = Mean value of elastic modulus

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Concrete design strength values

- 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 recommended (0.85 used in the UK for flexure and axial loading, but may be taken as 1.0 for all other phenomena, such as shear)
- α_{ct} = 1.0
- α_{cc} & α_{ct} are coefficients to take account of long term unfavourable effects resulting from the way the load is applied

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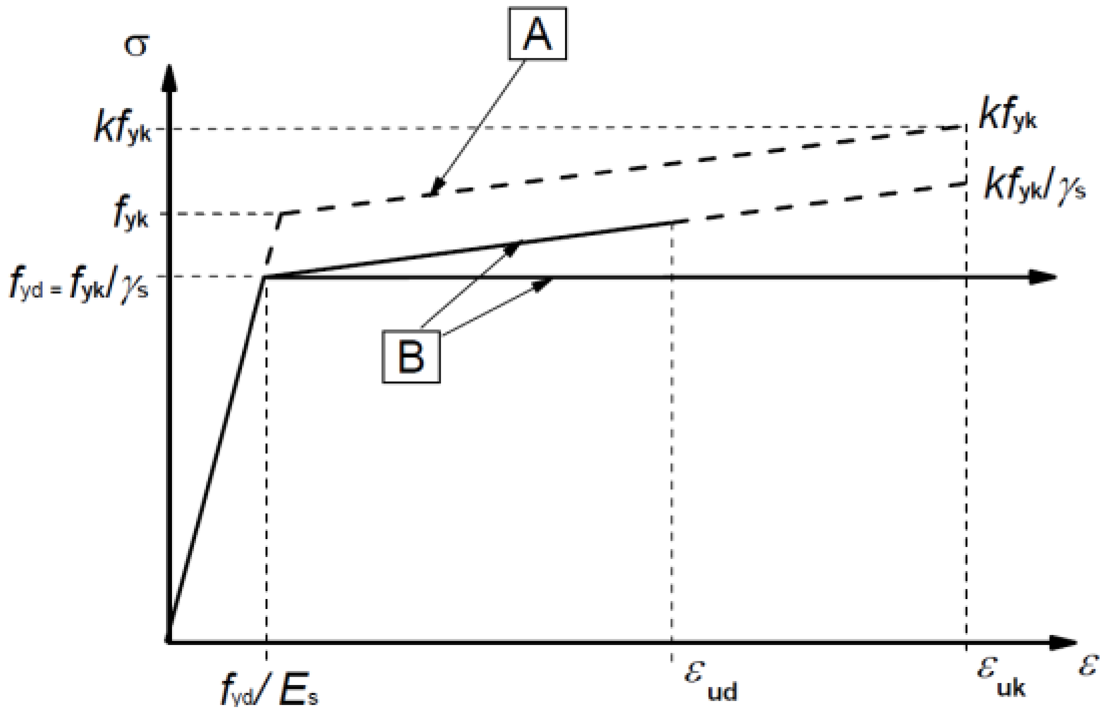
Materials, durability and structural analysis

MATERIALS - REINFORCEMENT

Reinforcement



$k = (f_t / f_y)_k$

A Idealised

B Design

Reinforcement

Product form	Bars and de-coiled rods			Wire Fabrics		
Class	A	B	C	A	B	C
Characteristic yield strength f_{yk} or $f_{0.2k}$ (MPa)	400 to 600					
Minimum value of $k = (f_t/f_y)_k$	1.05	1.08	1.15 <1.35	1.05	1.08	1.15 <1.35
Characteristic strain at maximum force. ε_{uk} (%)	2.5	5.0	7.5	2.5	5.0	7.5

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Materials, durability and structural analysis

DURABILITY

Durability – concrete members exposure classes

	Class	Description of the environment
	XO	No risk of corrosion or attack to concrete
Risk of corrosion to reinforcement	XC	Corrosion induced by carbonation
	XD	Corrosion induced by chlorides
	XS	Corrosion induced by chlorides from sea water
Attack to concrete	XF	Freeze/thaw attack
	XA	Chemical attack
	XM	Mechanical abrasion

Exposure classes: Classification of chemical and physical environmental conditions in which the structure is exposed in addition to the mechanical actions and which are not taken into account in verifications for ultimate and serviceability limit states.

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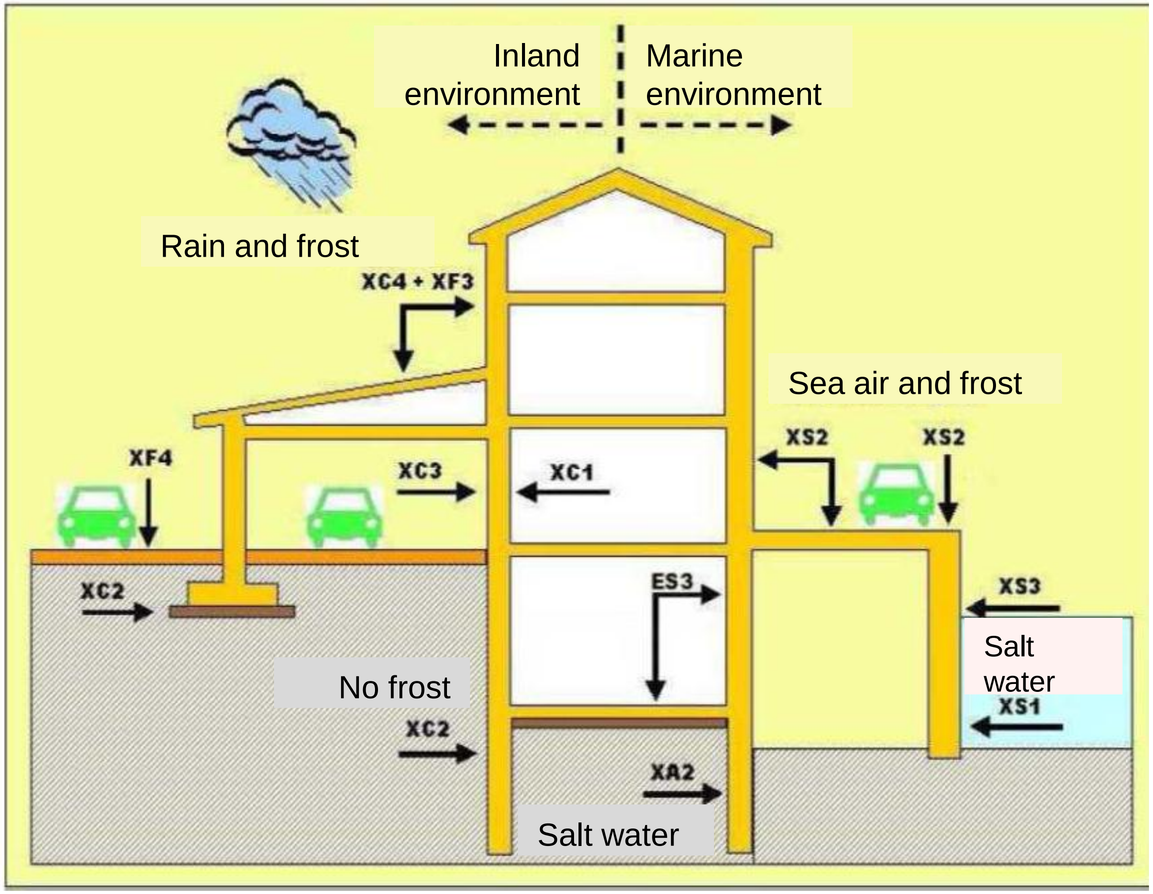
Exposure classes according to EN 1992-1-1 (risk of corrosion of reinforcement)

Class	Description of environment	Examples
no risk of corrosion or attack		
XO	for concrete without reinforcement, for concrete with reinforcement : very dry	concrete inside buildings with very low air humidity
Corrosion induced by carbonation		
XC1	dry or permanently wet	concrete inside buildings with low air humidity
XC2	wet, rarely dry	concrete surfaces subjected to long term water contact, foundations
XC3	moderate humidity	external concrete sheltered from rain
XC4	cyclic wet and dry	concrete surfaces subject to water contact not within class XC2
Corrosion induced by chlorides		
XD1	moderate humidity	concrete surfaces exposed to airborne chlorides
XD2	wet, rarely dry	swimming pools, members exposed to industrial waters containing chlorides
XD3	cyclic wet and dry	car park slabs, pavements, parts of bridges exposed to spray containing
Corrosion induced by chlorides from sea water		
XS1	exposed to airborne salt	structures near to or on the coast
XS2	permanently submerged	parts of marine structures
XS3	tidal, splash and spray zones	parts of marine structures

Exposure classes according to EN 1992-1-1 (risk of corrosion of reinforcement)

Class	Description of environment	Examples
Freeze/thaw attack		
XF1	moderate water saturation, without de-icing agent	Vertical concrete surfaces exposed to rain and freezing
XF2	moderate water saturation, with de-icing agent	Vertical concrete surfaces of road structures exposed to rain and freezing and airborne de-icing salts
XF3	high water saturation, without de-icing agent	Horizontal concrete surfaces exposed to rain and freezing
XF4	high water saturation, with de-icing agent or sea water	Road and bridge decks exposed to de-icing agents, concrete surfaces exposed to direct spray containing de-icing agents
Chemical attack		
XA1	slightly aggressive chemical environment according to EN 206, Table 2	Natural soils and ground water
XA2	moderate aggressive chemical environment according to EN 206, Table 2	
XA3	highly aggressive chemical environment according to EN 206, Table 2	

Example: Exposure classes



Nominal cover for durability

- The Nominal Cover, c_{nom}, is :

$$c_{nom} = c_{min} + \Delta c_{dev}$$

- where:
- $c_{min}=\max\{c_{min,b}; c_{min,dur}+c_{min,\gamma}-\Delta c_{dur,st}-\Delta c_{dur,add}; 10\text{mm}\}$

- $c_{min,b}$ = minimum requirements for bond
- $c_{min,dur}$ = minimum requirements for durability
- $c_{min,\gamma}$ = additional safety element (Recommended = 0mm)
- $\Delta c_{dur,st}$ = Reduction for stainless steel (Recommended = 0mm)
- $\Delta c_{dur,add}$ = Reduction for additional protection (Recommended value = 0mm)

Fire resistance should also be considered

Minimum cover $c_{min,dur}$

Table 4.4N: Values of minimum cover, $c_{min,dur}$, requirements with regard to durability for reinforcement steel in accordance with EN 10080.

Environmental Requirement for $c_{min,dur}$ (mm)							
Structural Class	Exposure Class according to Table 4.1						
	X0	XC1	XC2 / XC3	XC4	XD1 / XS1	XD2 / XS2	XD3 / XS3
S1	10	10	10	15	20	25	30
S2	10	10	15	20	25	30	35
S3	10	10	20	25	30	35	40
S4	10	15	25	30	35	40	45
S5	15	20	30	35	40	45	50
S6	20	25	35	40	45	50	55

From EN 1992-1-1 The recommended Structural Class (design working life of 50-years) is Structural Class S4

But from UK NA to EN 1992-1-1, $c_{min,dur}$ should be taken from BS 8500-1

4.4.1.2 (5)	Structural classification and values of minimum cover due to environmental conditions $c_{min,dur}$	Table 4.3N for structural classification Tables 4.4N and 4.5N for values of $c_{min,dur}$	(A1) Use BS 8500-1:2006, Tables A.5 and A.11 for recommendations for concrete quality for a particular exposure class and cover reinforcement c. (A1)
4.4.1.2 (6)	Value of $\Delta c_{dur,\gamma}$	0 mm	Use the recommended value
4.4.1.2 (7)	Value of $\Delta c_{dur,st}$	0 mm	0 mm unless justified by reference to specialist literature such as the Concrete Society's guidance on the use of stainless steel reinforcement [1].
4.4.1.2 (8)	Value of $\Delta c_{dur,add}$	0 mm	0 mm unless justified by reference to specialist literature
4.4.1.2 (13)	Value of k_1, k_2, k_3	k_1 = 5 mm k_2 = 10 mm k_3 = 15 mm	Use the recommended value
4.4.1.3 (1)P	Value of Δc_{dev}	10 mm	Use the recommended value
4.4.1.3 (3)	Value of Δc_{dev} under controlled conditions	Expressions (4.3N) and (4.4N)	Use the recommended values

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Concrete quality and cover to reinforcement for durability for an intended working life of at least 50-years according to BS 8500-1

Nominal cover [B]	Compressive strength class where recommended, maximum water-cement ratio and minimum cement or combination content for normal-weight concrete [C] with 20 mm maximum aggregate size [D]								Cement/combination types
mm	15 + Δc	20 + Δc	25 + Δc	30 + Δc	35 + Δc	40 + Δc	45 + Δc	50 + Δc	
Corrosion induced by carbonation (XC exposure classes)									
XC1	C20/25 0.70 240	C20/25 0.70 240	C20/25 0.70 240	C20/25 0.70 240	C20/25 0.70 240	C20/25 0.70 240	C20/25 0.70 240	C20/25 0.70 240	All in Table A.6
XC2	—	—	C25/30 0.65 260	C25/30 0.65 260	C25/30 0.65 260	C25/30 0.65 260	C25/30 0.65 260	C25/30 0.65 260	All in Table A.6
XC3/4	—	C40/50 0.45 340	C30/37 0.55 300	C28/35 0.60 280	C25/30 0.65 260	C25/30 0.65 260	C25/30 0.65 260	C25/30 0.65 260	All in Table A.6 except IVB-V
	—	—	C40/50 0.45 340	C30/37 0.55 300	C28/35 0.60 280	C25/30 0.65 260	C25/30 0.65 260	C25/30 0.65 260	IVB-V
Corrosion induced by chlorides (XS from sea water, XD other than sea water) *Also adequate for any associated carbonation induced corrosion (XC)*									
XD1	—	—	C40/50 0.45 360	C32/40 0.55 320	C28/35 0.60 300	C28/35 0.60 300	C28/35 0.60 300	C28/35 0.60 300	All in Table A.6
XS1	—	—	—	C45/55[E] 0.35[F] 380	C35/45[E] 0.45 360	C32/40[E] 0.50 340	C32/40[E] 0.50 340	C32/40[E] 0.50 340	CEM I, IIA, IIB-S, SRPC
	—	—	—	C40/50[E] 0.35[F] 380	C32/40[E] 0.45 360	C28/35 0.50 340	C25/30 0.55 320	C25/30 0.55 320	IIB-V, IIIA
	—	—	—	C32/40[E] 0.40 380	C25/30 0.50 340	C25/30 0.50 340	C25/30 0.55 320	C25/30 0.55 320	IIIB
	—	—	—	C32/40[E] 0.40 380	C28/35 0.50 340	C25/30 0.50 340	C25/30 0.55 320	C25/30 0.55 320	IVB-V
XD2 or XS2	—	—	—	C40/50[E] 0.40 380	C32/40[E] 0.50 340	C28/35 0.55 320	C28/35 0.55 320	C28/35 0.55 320	CEM I, IIA, IIB-S, SRPC
	—	—	—	C35/45[E] 0.40 380	C28/35 0.50 340	C25/30 0.55 320	C25/30 0.55 320	C25/30 0.55 320	IIB-V, IIIA
	—	—	—	C32/40[E] 0.40 380	C25/30 0.50 340	C20/25 0.55 320	C20/25 0.55 320	C20/25 0.55 320	IIIB, IVB-V

Durability - tolerances

- Δc_{dev} = allowance in design for deviation
- Generally this is taken as 10mm
- Δc_{dev} may be reduced when:
  - **QA system, which includes measuring concrete cover is used, then:**

    $10 \text{ mm} \geq \Delta c_{dev} \geq 5 \text{ mm}$
  - **where very accurate measurements are taken and non-conforming members are rejected (e.g. precast elements)**

    $10 \text{ mm} \geq \Delta c_{dev} \geq 0 \text{ mm}$

Overview of cover

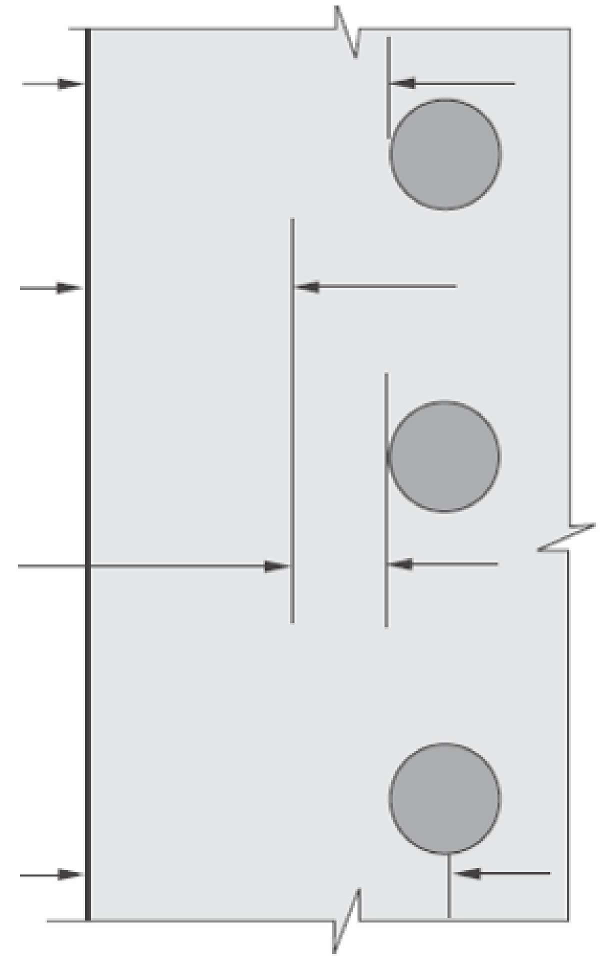
Nominal cover, c_{nom}

Minimum cover, c_{min}

$c_{min} = \max \{c_{min,b};\ c_{min,dur};\ 10\ \text{mm}\}$

Allowance for deviation, Δc_{dev}

Axis distance, *a* (Fire protection)



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Materials, durability and structural analysis

STRUCTURAL ANALYSIS

Analysis

The following types of analysis may be used:

- Linear elastic
- Linear elastic with limited redistribution (up to 30%)
- Plastic analysis (e.g. yield line, strut and tie)
- Non-linear behaviour

The following principles apply:

- Plane sections remain plane
- In monolithic construction, maximum hogging moment can be taken at face of support

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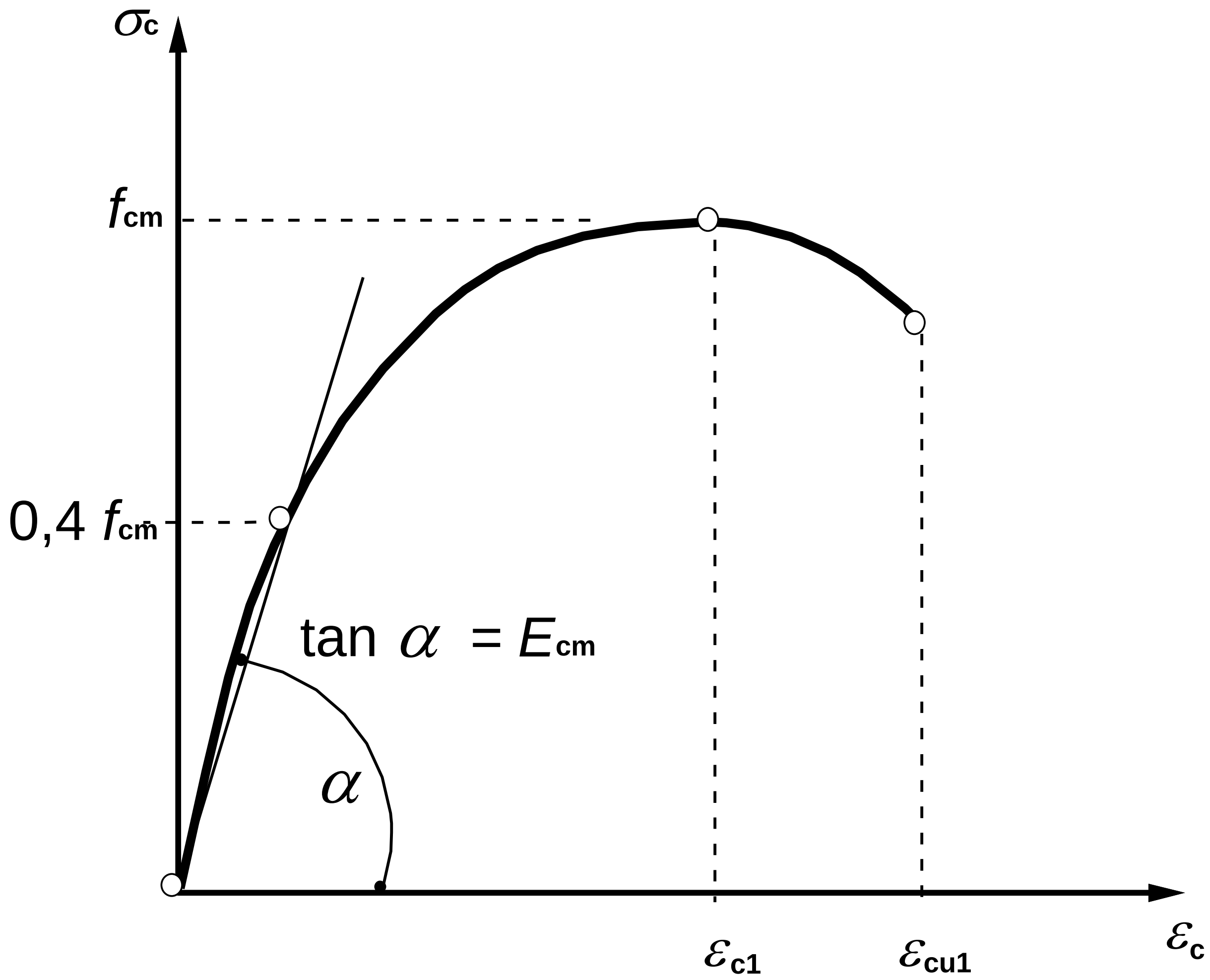
Analysis

- Linear elastic analysis may be used for both ULS and SLS and assuming:
  - **uncracked cross sections**
  - **linear stress-strain relationships**
  - **mean value of the modulus of elasticity**

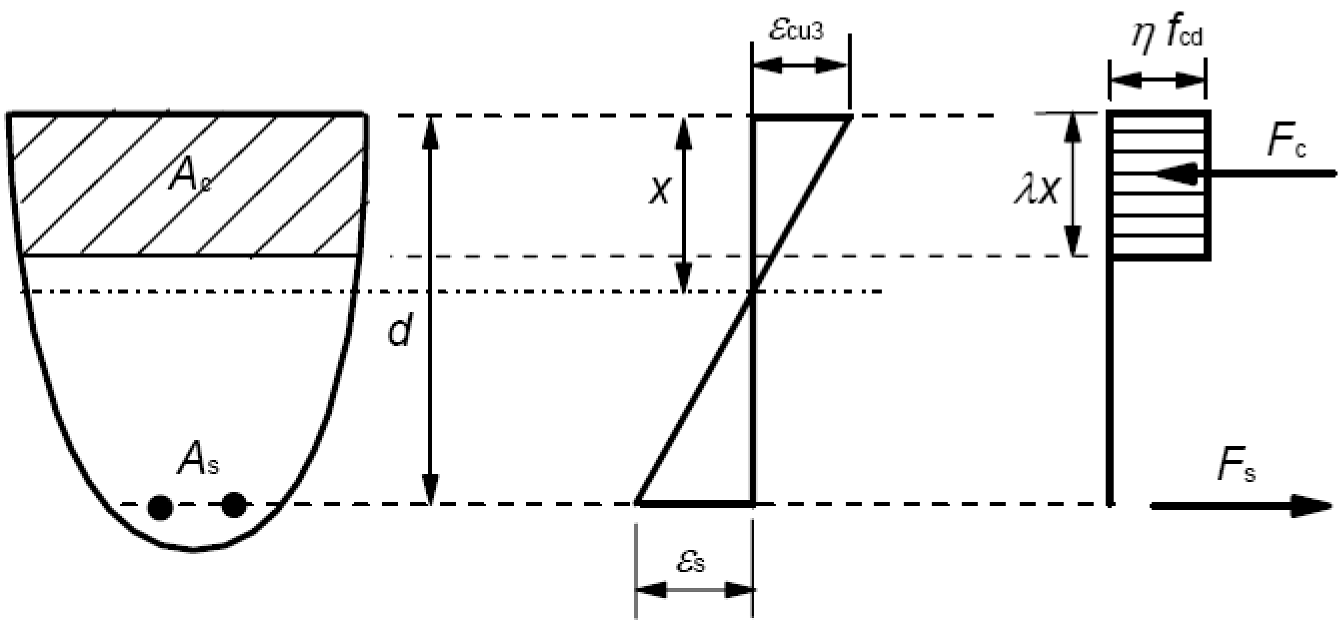
For thermal deformation, settlement and shrinkage effects at ULS a reduced stiffness corresponding to cracked sections may be assumed.

Flexure design

Stress-stain relationship for concrete



Rectangular stress distribution



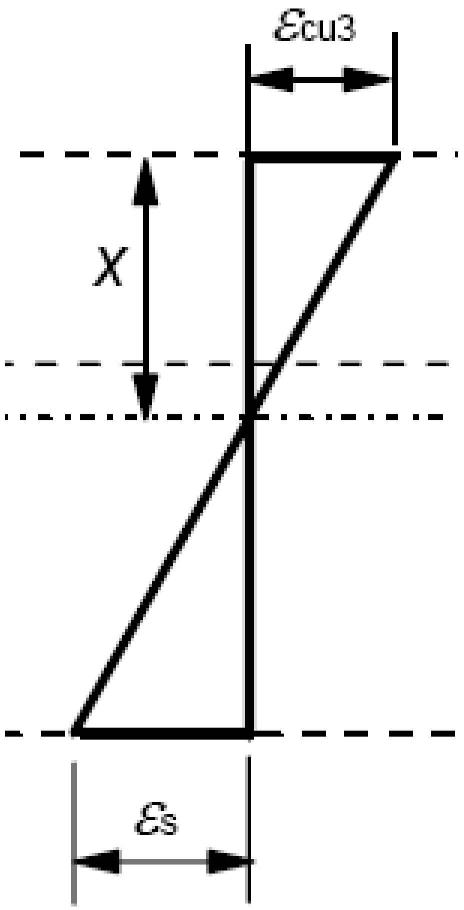
- For grades of concrete up to C50/60
  - $\varepsilon_{cu} = 0.0035$
  - Reduction factor $\eta = 1$
  - $\lambda = 0.8$.

Ensuring ductile failure

- To ensure that the steel reaches yield before the concrete crushes the depth to the neutral axis should be limited.

- Based on the UK recommended values for NDPs, for buildings the limiting value is:
- $x/d \leq 0.45$ ($f_{ck} \leq 50$)

- These apply when there is no redistribution



Shear design

Eurocode 2 approach to shear

Three approaches to shear in Eurocode 2:

1. Members not requiring design shear reinforcement
   - Usually used for slabs

2. Members requiring design shear reinforcement
   - Usually used for beams

3. Punching shear
   - Usually used for flat slabs

Members without shear reinforcement

- The shear resistance of concrete without shear reinforcement (links) is given by the following expression:
- $V_{Rd,c} = [C_{Rd,c}\, k(100\, \rho_l\, f_{ck})^{1/3} + k_1 \sigma_{cp}]\, b_w d$

NDPs

- with a minimum of
- $V_{Rd,c} = (v_{min} + k_1 \sigma_{cp})\, b_w d$

Allows for axial loads eg prestress

- where
- $k = 1 + \sqrt{(200/d)} \leq 2$
- $\rho_l = A_s/(bd)$

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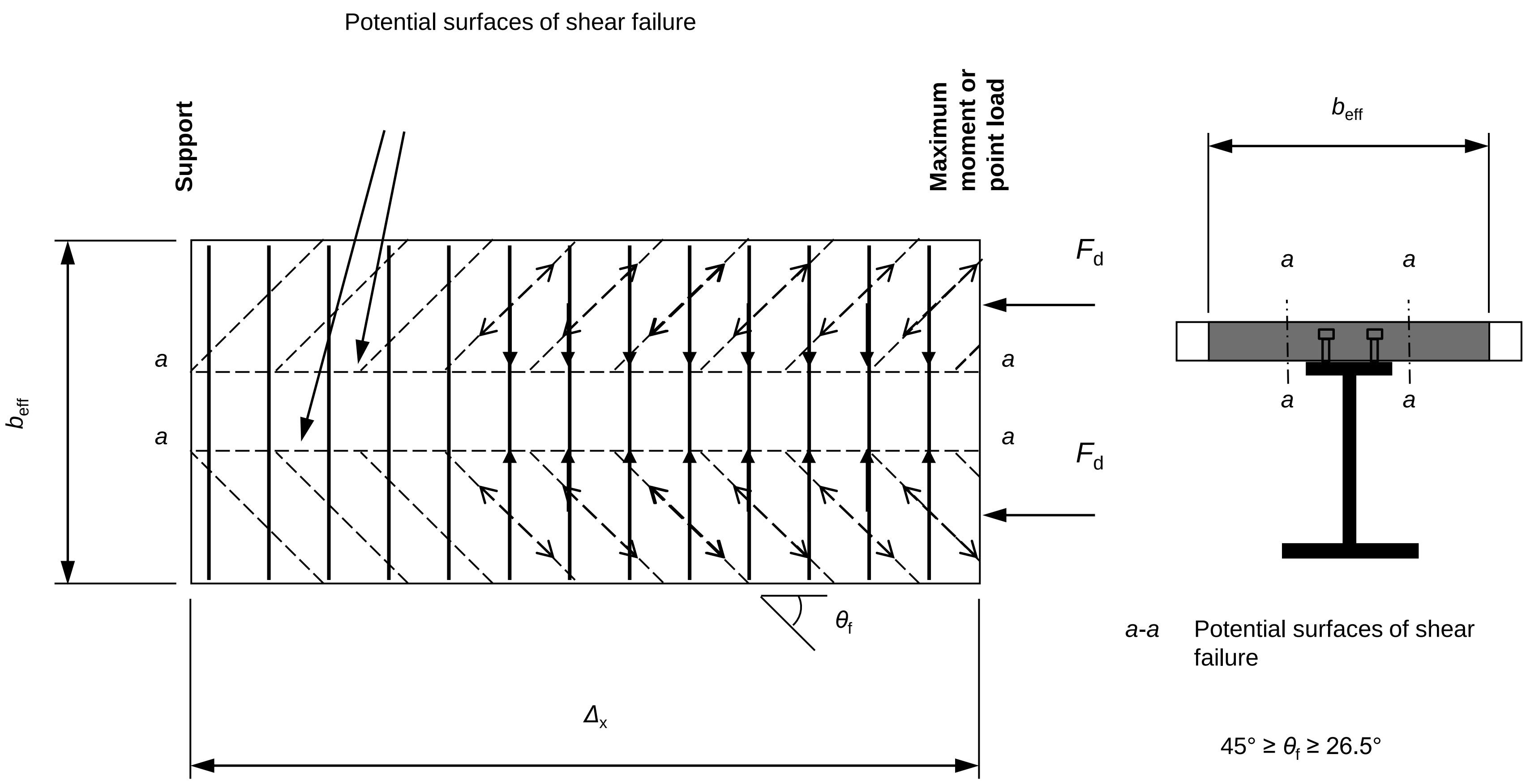
Shear reinforcement (variable strut inclination method)



$45° \geq \theta_f \geq 26.5°$

Axial resistance

Design moments

Geometric imperfections

Either:

1. Analyze whole frame and include effective of geometric imperfections.

OR

2. From analysis add the effect of geometric imperfections to individual members, $e_i = l_0/400$

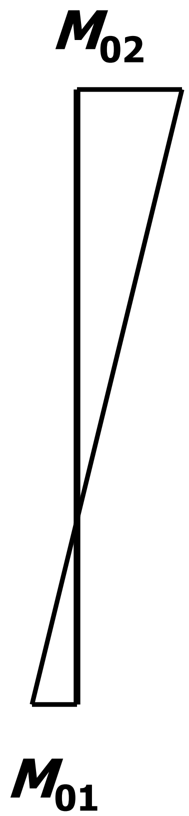
- Also:
- $e_0 = h/30 \geq 20$ mm

Design moments

- M_{01} and M_{02} should have the same sign if they give tension on the same side, otherwise opposite signs. Furthermore, $|M_{02}| \geq |M_{01}|$
- The first order design moments are then:
- $M_{02} = \text{Max}\{|M_{top}|;|M_{bot}|\} + e_i N_{Ed} \geq e_0 N_{Ed}$
- $M_{01} = \text{Min}\ \{|M_{top}|;|M_{bot}|\}$

- The second order design moments are:
- $M_2 = N_{Ed}\ e_2$

e_2 related to, *inter alia*: effective length, reinforcement ratio, slenderness, utilization of column, creep ratio



Non-contradictory complimentary information

PD 6687:2006

PUBLISHED DOCUMENT

Background paper to the UK National Annexes to BS EN 1992-1

British Standards

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PD 6687-2:2008

PUBLISHED DOCUMENT

Recommendations for the design of structures to BS EN 1992-2:2005

British Standards

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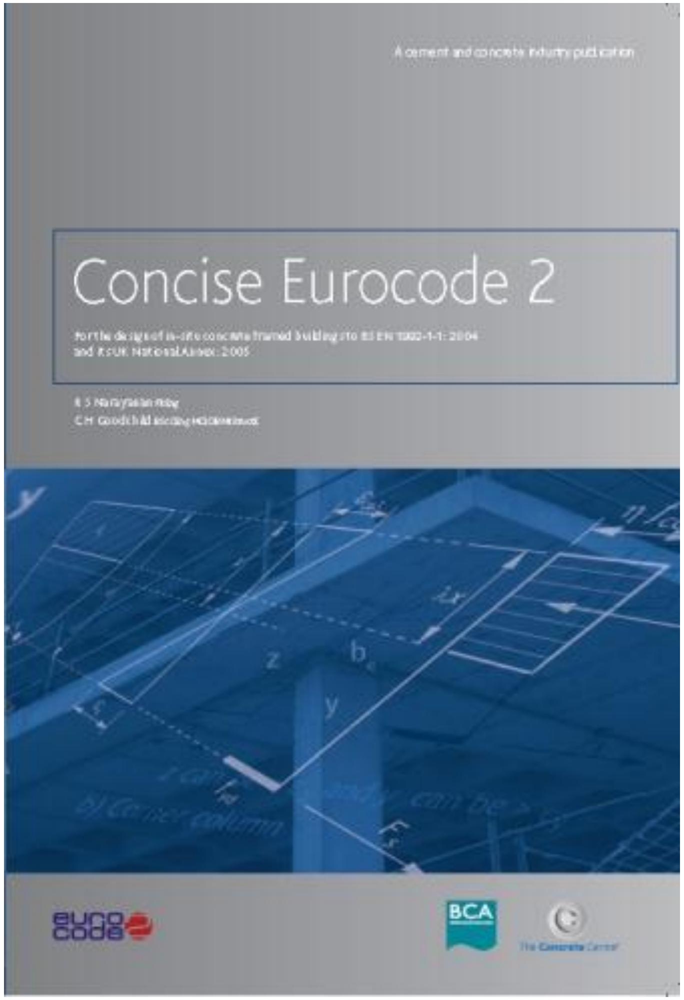
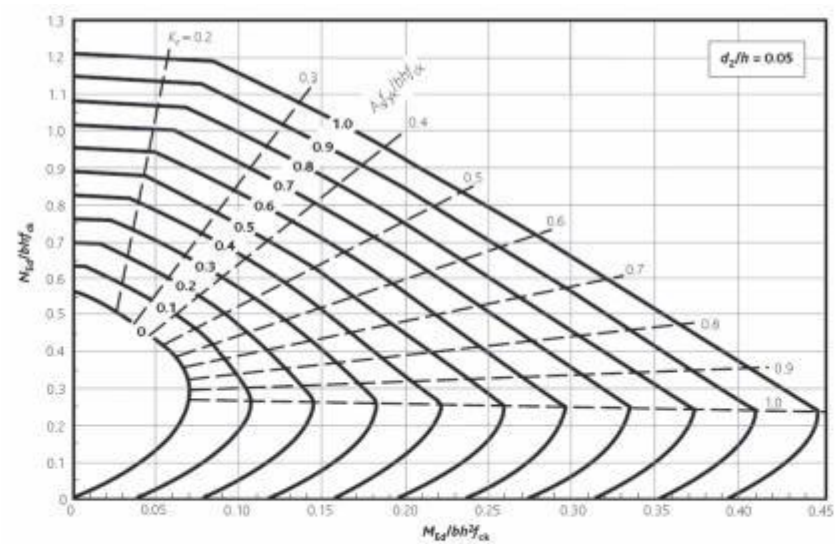
Simple design tools given Concise Eurocode 2 by UK Cement and Concrete Industry





Serviceability

Serviceability

- There are three areas to consider for SLS:

1. Stress limitation

   PD 6687-1, 2.20: "*Stress checks in reinforced concrete members have not been required in the UK for the past 50 years or so and there has been no known adverse effect. Provided that the design has been carried out properly for ultimate limit state there will be no significant effect at serviceability in respect of longitudinal cracking*"

2. Crack control

3. Deflection control

EN 1992-1-1, 7.1(1): *Other limit states (such as vibration) may be of importance in particular structures but are not covered in this Standard*.

Crack control

Cracking is controlled by:

- Providing minimum reinforcement areas
- Limiting bar size and spacing

A minimum area should always be provided.

Limiting size and spacing can be checked by

- Control of cracking without direct calculation (simplified method)

OR

- Calculation of crack widths

Recommended crack width values w_{max} (mm)

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	0.2
XC2, XC3, XC4	0.3	0.2
XD1, XD2, XD3, XS1, XS2, XS3		Decompression

The decompression limit requires that all parts of the bonded tendons or duct lie at least 25 mm within concrete in compression

Deflection

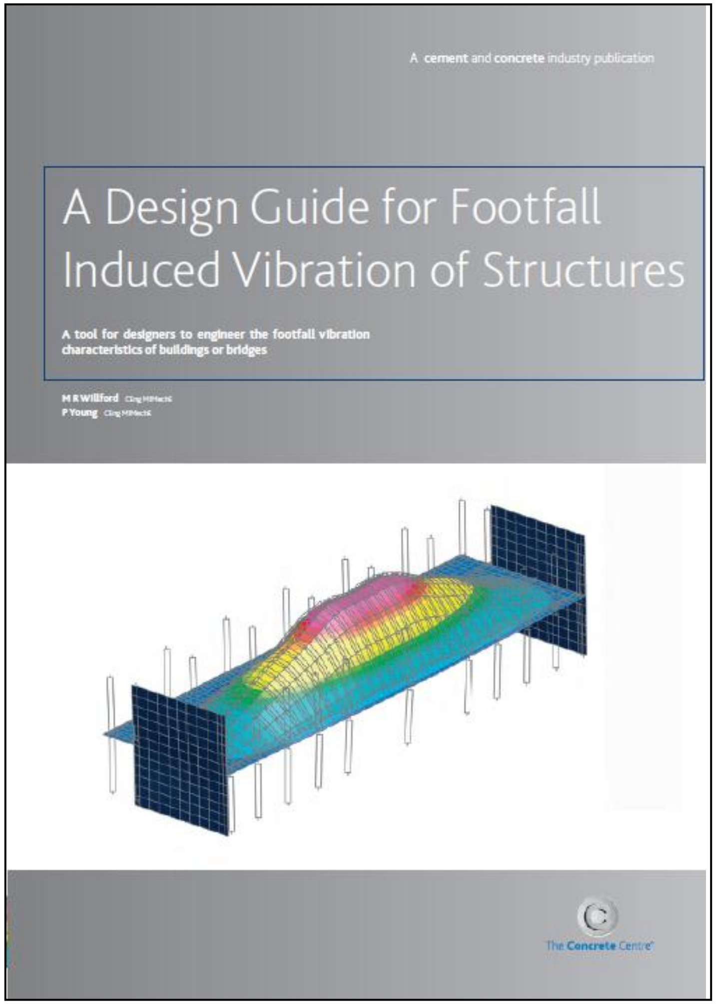
Appropriate deflection limits are:

- Deflection under the action of *quasi permanent* loads ≤ span/250
- Deflection after construction that could damage supported elements (based on *quasi permanent* loads) ≤ span/500

Deflection can be checked by:

- Limiting span-to-depth ratio
- Calculating deflections

Design guide for vibrations on concrete floors



- Modal superposition method (very similar to SCI P354)
- Simplified and approximate method (for hand calculations)

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