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

- EN 1990 Basis of design
- EN 1991 Actions
- EN 1992-1-1 General Rules and Buildings
- EN 1992-2 Bridges
- EN 1992-3 Water retaining structures
- EN 13670 Execution of structures
- National Application Document
- EN 1997 Geotechnical
- EN 206-1 Specifying concrete
- EN 13669 Pre-cast concrete
- EN 1992-1-2 Fire
- National Application Document
- EN 10080 Reinforcing Steels

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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 C\(x/y\), 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 L\(Cx/y\))

• Maximum value of characteristic strength
  • C90/105 for buildings
  • C70/85 for bridges
## Concrete properties

<table>
<thead>
<tr>
<th>Strength classes for concrete</th>
<th>12</th>
<th>16</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
<th>40</th>
<th>45</th>
<th>50</th>
<th>55</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{ck}$ (MPa)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f_{ck,cube}$ (MPa)</td>
<td>15</td>
<td>20</td>
<td>25</td>
<td>30</td>
<td>37</td>
<td>45</td>
<td>50</td>
<td>55</td>
<td>60</td>
<td>67</td>
<td>75</td>
<td>85</td>
<td>95</td>
<td>105</td>
</tr>
<tr>
<td>$f_{cm}$ (MPa)</td>
<td>20</td>
<td>24</td>
<td>28</td>
<td>33</td>
<td>38</td>
<td>43</td>
<td>48</td>
<td>53</td>
<td>58</td>
<td>63</td>
<td>68</td>
<td>78</td>
<td>88</td>
<td>98</td>
</tr>
<tr>
<td>$f_{ctm}$ (MPa)</td>
<td>1.6</td>
<td>1.9</td>
<td>2.2</td>
<td>2.6</td>
<td>2.9</td>
<td>3.2</td>
<td>3.5</td>
<td>3.8</td>
<td>4.1</td>
<td>4.2</td>
<td>4.4</td>
<td>4.6</td>
<td>4.8</td>
<td>5.0</td>
</tr>
<tr>
<td>$E_{cm}$ (GPa)</td>
<td>27</td>
<td>29</td>
<td>30</td>
<td>31</td>
<td>33</td>
<td>34</td>
<td>35</td>
<td>36</td>
<td>37</td>
<td>38</td>
<td>39</td>
<td>41</td>
<td>42</td>
<td>44</td>
</tr>
</tbody>
</table>

- $f_{ck}$ = 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
Concrete design strength values

• Design compressive strength, $f_{cd}$
  
  \[ f_{cd} = \alpha_{cc} \frac{f_{ck}}{\gamma_c} \]

• Design tensile strength, $f_{ctd}$
  
  \[ f_{ctd} = \alpha_{ct} \frac{f_{ctk,0.05}}{\gamma_c} \]

• $\alpha_{cc} = 1.0$ 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)

• $\alpha_{ct} = 1.0$

• $\alpha_{cc}$ & $\alpha_{ct}$ are coefficients to take account of long term unfavourable effects resulting from the way the load is applied
Materials, durability and structural analysis

MATERIALS - REINFORCEMENT
Reinforcement

\[ k = \left( \frac{f_t}{f_y} \right)_k \]

- A: Idealised
- B: Design
## Reinforcement

<table>
<thead>
<tr>
<th>Class</th>
<th>Bars and de-coiled rods</th>
<th>Wire Fabrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>400 to 600</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>1.05</td>
<td>1.08</td>
</tr>
<tr>
<td>C</td>
<td>1.15 / 1.35</td>
<td>1.15 / 1.35</td>
</tr>
<tr>
<td>A</td>
<td>2.5</td>
<td>5.0</td>
</tr>
<tr>
<td>B</td>
<td>7.5</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>2.5</td>
<td>5.0</td>
</tr>
</tbody>
</table>
Materials, durability and structural analysis
## Durability – concrete members exposure classes

<table>
<thead>
<tr>
<th>Class</th>
<th>Description of the environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>XO</td>
<td>No risk of corrosion or attack to concrete</td>
</tr>
<tr>
<td>XC</td>
<td>Corrosion induced by carbonation</td>
</tr>
<tr>
<td>XD</td>
<td>Corrosion induced by chlorides</td>
</tr>
<tr>
<td>XS</td>
<td>Corrosion induced by chlorides from sea water</td>
</tr>
<tr>
<td>XF</td>
<td>Freeze/thaw attack</td>
</tr>
<tr>
<td>XA</td>
<td>Chemical attack</td>
</tr>
<tr>
<td>XM</td>
<td>Mechanical abrasion</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Class</th>
<th>Description of environment</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>no risk of corrosion or attack</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>XO</strong></td>
<td>for concrete without reinforcement, for concrete with reinforcement: very dry</td>
<td>concrete inside buildings with very low air humidity</td>
</tr>
</tbody>
</table>

**Corrosion induced by carbonation**

<table>
<thead>
<tr>
<th>Class</th>
<th>Description of environment</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>XC1</strong></td>
<td>dry or permanently wet</td>
<td>concrete inside buildings with low air humidity</td>
</tr>
<tr>
<td><strong>XC2</strong></td>
<td>wet, rarely dry</td>
<td>concrete surfaces subjected to long term water contact, foundations</td>
</tr>
<tr>
<td><strong>XC3</strong></td>
<td>moderate humidity</td>
<td>external concrete sheltered from rain</td>
</tr>
<tr>
<td><strong>XC4</strong></td>
<td>cyclic wet and dry</td>
<td>concrete surfaces subject to water contact not within class XC2</td>
</tr>
</tbody>
</table>

**Corrosion induced by chlorides**

<table>
<thead>
<tr>
<th>Class</th>
<th>Description of environment</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>XD1</strong></td>
<td>moderate humidity</td>
<td>concrete surfaces exposed to airborne chlorides</td>
</tr>
<tr>
<td><strong>XD2</strong></td>
<td>wet, rarely dry</td>
<td>swimming pools, members exposed to industrial waters containing chlorides</td>
</tr>
<tr>
<td><strong>XD3</strong></td>
<td>cyclic wet and dry</td>
<td>car park slabs, pavements, parts of bridges exposed to spray containing</td>
</tr>
</tbody>
</table>

**Corrosion induced by chlorides from sea water**

<table>
<thead>
<tr>
<th>Class</th>
<th>Description of environment</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>XS1</strong></td>
<td>exposed to airborne salt</td>
<td>structures near to or on the coast</td>
</tr>
<tr>
<td><strong>XS2</strong></td>
<td>permanently submerged</td>
<td>parts of marine structures</td>
</tr>
<tr>
<td><strong>XS3</strong></td>
<td>tidal, splash and spray zones</td>
<td>parts of marine structures</td>
</tr>
</tbody>
</table>
Exposure classes according to EN 1992-1-1
(risk of corrosion of reinforcement)

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

- Salt water
- No frost
- Salt water
- Sea air and frost
- Inland environment
- Marine environment

Rain and frost

Inland environment

Marine environment
Nominal cover for durability

• The Nominal Cover, $c_{\text{nom}}$, is:

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

• where:

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

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

Fire resistance should also be considered
Minimum cover $c_{\text{min, dur}}$

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, $c_{\text{min, dur}}$ should be taken from BS 8500-1

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

<table>
<thead>
<tr>
<th>Environmental Requirement for $c_{\text{min, dur}}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Structural Class</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>S1</td>
</tr>
<tr>
<td>S2</td>
</tr>
<tr>
<td>S3</td>
</tr>
<tr>
<td>S4</td>
</tr>
<tr>
<td>S5</td>
</tr>
<tr>
<td>S6</td>
</tr>
</tbody>
</table>

---

4.4.1.2 (5) Structural classification and values of minimum cover due to environmental conditions $c_{\text{min,dur}}$

|  | Structural classification and values of minimum cover due to environmental conditions $c_{\text{min,dur}}$ |
|  | Table 4.3N for structural classification Tables 4.4N and 4.5N for values of $c_{\text{min,dur}}$ |
|  | Use BS 8500-1:2006, Tables A.5 and A.11 for recommendations for concrete quality for a particular exposure class and cover reinforcement $c$. |

4.4.1.2 (6) Value of $\Delta c_{\text{dur},y}$

|  | 0 mm |
|  | Use the recommended value |

4.4.1.2 (7) Value of $\Delta c_{\text{dur},st}$

|  | 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 $\Delta c_{\text{dur},add}$

|  | 0 mm |
|  | 0 mm unless justified by reference to specialist literature |

4.4.1.3 (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 (13) Value of $\Delta c_{\text{dur}}$ 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

<table>
<thead>
<tr>
<th>Nominal cover (mm)</th>
<th>Compressive strength class where recommended, maximum water-cement ratio and minimum cement or combination content for normal-weight concrete (1) with 20 mm maximum aggregate size (2)</th>
<th>Cement/comboination types</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Corrosion induced by carbonation (XC exposure classes)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Corrosion induced by chlorides (XS from sea water, XD other than sea water) Also adequate for any associated carbonation induced corrosion (XC)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>All in Table A.6</td>
</tr>
<tr>
<td>XC1</td>
<td>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</td>
<td>All in Table A.6</td>
</tr>
<tr>
<td>XC2</td>
<td>— — 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</td>
<td>All in Table A.6</td>
</tr>
<tr>
<td>XC3/4</td>
<td>— C40/50 0.45 340 C30/37 0.55 300 C28/35 0.60 280 C28/35 0.60 280 C28/35 0.60 280 C28/35 0.60 280 C28/35 0.60 280</td>
<td>All in Table A.6 except IVB-V</td>
</tr>
</tbody>
</table>

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Durability - tolerances

• $\Delta c_{\text{dev}}$ = allowance in design for deviation
• Generally this is taken as 10mm
• $\Delta c_{\text{dev}}$ may be reduced when:
  • QA system, which includes measuring concrete cover is used, then:
    $10 \text{ mm} \geq \Delta c_{\text{dev}} \geq 5 \text{ mm}$
  • where very accurate measurements are taken and non-conforming members are rejected (e.g. precast elements)
    $10 \text{ mm} \geq \Delta c_{\text{dev}} \geq 0 \text{ mm}$
Overview of cover

Nominal cover, $c_{\text{nom}}$

Minimum cover, $c_{\text{min}}$

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

Allowance for deviation, $\Delta c_{\text{dev}}$

Axis distance, $a$ (Fire protection)
Materials, durability and 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
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

\[ \tan \alpha = E_{cm} \]

\[ f_{cm} \]

\[ 0.4 f_{cm} \]

\[ \varepsilon_{c1} \]

\[ \varepsilon_{cu1} \]
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:

\[ V_{Rd,c} = [C_{Rd,c} k(100 \rho_1 f_{ck})^{1/3} + k_1 \sigma_{cp}] b_w d \]

with a minimum of

\[ V_{Rd,c} = (v_{min} + k_1 \sigma_{cp}) b_w d \]

where

- \( k = 1 + \sqrt{(200/d)} \leq 2 \)
- \( \rho_1 = A_s/(bd) \)

Allows for axial loads eg prestress

NDPs
Shear reinforcement (variable strut inclination method)

Potential surfaces of shear failure

Support

Maximum moment or point load

$b_{eff}$

$F_d$

$a$

$\Delta_x$

$\theta_f$

$45^\circ \geq \theta_f \geq 26.5^\circ$

a-a Potential surfaces of shear failure
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:
   - \( e_0 = h / 30 \geq 20 \text{ mm} \)
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:
  - $M_{02} = \text{Max}\{ |M_{\text{top}}|; |M_{\text{bot}}| \} + e_i N_{Ed} \geq e_0 N_{Ed}$
  - $M_{01} = \text{Min}\{ |M_{\text{top}}|; |M_{\text{bot}}| \}$

- 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
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 $w_{\text{max}}$ (mm)

<table>
<thead>
<tr>
<th>Exposure Class</th>
<th>Reinforced members and prestressed members with unbonded tendons</th>
<th>Prestressed members with bonded tendons</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Quasi-permanent load combination</td>
<td>Frequent load combination</td>
</tr>
<tr>
<td>X0, XC1</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>XC2, XC3, XC4</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>XD1, XD2, XD3, XS1, XS2, XS3</td>
<td>Decompression</td>
<td></td>
</tr>
</tbody>
</table>

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 $\leq \text{span}/250$
- Deflection after construction that could damage supported elements (based on *quasi permanent* loads) $\leq \text{span}/500$

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)

Concrete Centre CCIP-016 (2006)