HOW TO DESIGN

CONCRETE STRUCTURES

Columns
Instructions for the Members of BIBM, CEMBUREAU, EFCA and ERMCO:

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5. Columns

Introduction

This should be redrafted as appropriate in each country

Designing to Eurocode 2

This guide is intended to assist engineers with the design of columns and walls to Eurocode 2. It sets out a design procedure to follow and gives useful commentary on the provisions within the Eurocode.

Eurocode 2 does not contain the derived formulae; this is because it has been European practice to give principles and general application rules in the codes and for detailed application rules to be presented in other sources such as textbooks or guidance documents.

The first guide in this series, How to design concrete structures using Eurocode 2: Introduction, provides an overview of Eurocodes, including terminology.

Where NDPs occur in the text in this publication, recommended values in EN 1992 are used and highlighted in yellow. The UK values have been used for NDPs embedded in figures and charts and the relevant NDPs are scheduled separately to assist other users in adapting the figures and charts. (Derivations can be found at www.eurocode2.info.) A full list of symbols related to column design is given at the end of this guide.

Design procedure

A procedure for carrying out the detailed design of braced columns (i.e. columns that do not contribute to resistance of horizontal actions) is shown in Table 1. This assumes that the column dimensions have previously been determined during conceptual design or by using quick design methods. Column sizes should not be significantly different from those obtained using current practice. Steps 1 to 4 of Table 1 are covered by earlier guides in this series and the next step is therefore to consider fire resistance.

Fire resistance

Eurocode 2, Part 1–2: Structural fire design, gives a choice of advanced, simplified or tabular methods for determining fire resistance of columns. Using tables is the fastest method for determining the minimum dimensions and cover for columns. There are, however, some restrictions and if these apply further guidance can be obtained from specialist literature. The simplified method may give more economic columns, especially for small columns and/or high fire resistance periods.

Rather than giving a minimum cover, the tabular method is based on nominal axis distance, a (see Figure 1). This is the distance from the centre of the main reinforcing bar to the surface of the member.
Table 1

<table>
<thead>
<tr>
<th>Step</th>
<th>Task</th>
<th>Further guidance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Determine design life</td>
<td>Getting started</td>
</tr>
<tr>
<td>2</td>
<td>Assess actions on the column</td>
<td>Getting started</td>
</tr>
<tr>
<td>3</td>
<td>Determine which combinations of actions apply</td>
<td>Introduction to Eurocodes</td>
</tr>
<tr>
<td>4</td>
<td>Assess durability requirements and determine concrete strength</td>
<td>Getting started BS 8500. 2002</td>
</tr>
<tr>
<td>5</td>
<td>Check cover requirements for appropriate fire resistance period</td>
<td>Getting started and Table 2 of this guide BS EN 1992-1-2</td>
</tr>
<tr>
<td>6</td>
<td>Calculate min. cover for durability, fire and bond requirements</td>
<td>Getting started BS EN 1992-1-1 CL. 4.4.1</td>
</tr>
<tr>
<td>7</td>
<td>Analyze structure to obtain critical moments and axial forces</td>
<td>Getting started and 'structural analysis' section of this guide BS EN 1992-1-1 section 5</td>
</tr>
<tr>
<td>8</td>
<td>Check slenderness</td>
<td>See Figures 2 and 3 of this guide BS EN 1992-1-1 section 5.8</td>
</tr>
<tr>
<td>9</td>
<td>Determine area of reinforcement required</td>
<td>See Figures 2 and 3 of this guide BS EN 1992-1-1 section 6.1</td>
</tr>
<tr>
<td>10</td>
<td>Check spacing of bars</td>
<td>'Rules for spacing' section of this guide BS EN 1992-1-1 sections 8 and 9</td>
</tr>
</tbody>
</table>

**Note**

NA = National Annex.

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Table 2

Minimum column dimensions and axis distances for fire resistance

<table>
<thead>
<tr>
<th>Standard fire resistance</th>
<th>Minimum dimensions (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Column width based axis distance, a, of the main bars</td>
</tr>
<tr>
<td></td>
<td>Column exposed on more than one side (f = 0.5)</td>
</tr>
<tr>
<td></td>
<td>μ = 0.5</td>
</tr>
<tr>
<td>R 60</td>
<td>200/36</td>
</tr>
<tr>
<td>R 90</td>
<td>300/31</td>
</tr>
<tr>
<td>R 120</td>
<td>300/45</td>
</tr>
<tr>
<td>R 240</td>
<td>300/45a</td>
</tr>
<tr>
<td></td>
<td>450/40a</td>
</tr>
</tbody>
</table>

**Note**

The table is taken from BS EN 1992-1-2 Table 5.2a (method A) and is valid under the following conditions:

1. The effective length of a closed column under fire conditions (f = 3m). The value of f may be taken as 50% of the actual length for intermediate floors and between 50% and 70% of the actual length for the upper floor column.
2. The fire action eccentricity under fire conditions should be ≤ 0.15f (or f). Alternatively use method B (see Eurocode 2, Part 1-2, Table 5.2b). The eccentricity under fire conditions may be taken as that used in normal temperature design.
3. The reinforcement area outside the lap locations does not exceed 4% of the concrete cross section.
4. w1 is the ratio of the design axial load under fire conditions to the design resistance of the column at normal temperature conditions w1 may conservatively be taken as 0.7.

**Key**

a Minimum 8 bars.

b Method B may be used which includes 600/70 for R 240 and μ = 0.7. See BS EN 1992-1-2 Table 5.2b.

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Figure 1

Section through structural member, showing nominal axis distance a

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Table 3

Minimum reinforced concrete wall dimensions and axis distances for load-bearing for fire resistance, using method A

<table>
<thead>
<tr>
<th>Standard fire resistance</th>
<th>Minimum dimensions (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wall thickness/axis distance, a, of the main bars</td>
</tr>
<tr>
<td></td>
<td>Wall exposed on one side (μ = 0.1)</td>
</tr>
<tr>
<td>REI 60</td>
<td>130/10a</td>
</tr>
<tr>
<td>REI 90</td>
<td>140/25</td>
</tr>
<tr>
<td>REI 120</td>
<td>160/35</td>
</tr>
<tr>
<td>REI 240</td>
<td>270/60</td>
</tr>
</tbody>
</table>

**Notes**

1. The table is taken from BS EN 1992-1-2 Table 5.2a.
2. See note 4 of Table 2.

**Key**

a Normally the requirements of BS EN 1992-1-1 will determine the cover.
It is a nominal (not minimum) dimension, and the
designer should ensure that:
\[ a \geq c_{\text{nom}} + \phi_{\text{link}} + \phi_{\text{bar}}/2. \]

For columns there are two tables given in Eurocode 2
Part 1–2 that present methods A and B. Both are
equally applicable, although method A has smaller
limits on eccentricity than method B.

Method A is slightly simpler and is presented in Table 2;
limits of applicability are given in the notes. Similar data
for load-bearing walls is given in Table 3.

For columns supporting the uppermost storey, the
eccentricity will often exceed the limits for both methods
A and B. In this situation Annex C of Eurocode 2, Part
1–2 may be used. Alternatively, consideration can be
given to treating the column as a beam for determining
the design fire resistance.

Column design

A flow chart for the design of braced columns is shown
in Figure 2. For slender columns, Figure 3 will also be
required.

Structural analysis

The type of analysis should be appropriate to the
problem being considered. The following may be used:
linear elastic analysis, linear elastic analysis with limited
redistribution, plastic analysis and non-linear analysis.
Linear elastic analysis may be carried out assuming
cross sections are uncracked (i.e. concrete section
properties), using linear stress-strain relationships and
assuming mean values of long-term elastic modulus.
For the design of columns the elastic moments from the
frame action should be used without any redistribution.
For slender columns a non-linear analysis may be
carried out to determine the second order moments;
alternatively use the moment magnification method
(CI 5.8.7.3) or nominal curvature method (CI 5.8.8) as
illustrated in Figure 3.

Design moments

The design bending moment is illustrated in Figure 4
and defined as:
\[ M_{\text{Ed}} = \max \{ M_{02}, M_{0e} + M_2, M_{01} + 0.5 M_2 \} \]
where:
\[ M_{01} = \min \{ |M_{\text{top}}|, |M_{\text{bottom}}| \} + e_1 N_{\text{Ed}} \]
\[ M_{02} = \max \{ |M_{\text{top}}|, |M_{\text{bottom}}| \} + e_1 N_{\text{Ed}} \]
\[ e_1 = \max \{ l/400, h/30, 20 \} \text{ (units to be}
\text{consistent with that used for moments).} \]
\[ M_{\text{top, bottom}} = \text{Moments at the top and bottom of the}
\text{column} \]
\[ M_{0e} = 0.6 M_{02} + 0.4 M_{01} \geq 0.4 M_{02} \]
\[ M_2 = N_{\text{Ed}} e_2 \text{ where } N_{\text{Ed}} \text{ is the design axial}
\text{load and } e_2 \text{ is deflection due to}
\text{second order effects} \]
\[ M_{01} \text{ and } M_{02} \text{ should be positive if they give tension on}
\text{the same side.} \]

A non-slender column can be designed ignoring second
order effects and therefore the ultimate design moment,
\[ M_{\text{Ed}} = M_{02}. \]

The calculation of the eccentricity, \( e_2 \), is not simple and
is likely to require some iteration to determine the
deflection at approximately mid-height, \( e_2 \). Guidance is
given in Figure 3.
Effective length

Figure 5 gives guidance on the effective length of the column. However, for most real structures Figures 5f and 5g only are applicable and Eurocode 2 provides two expressions to calculate the effective length for these situations. Expression (5.15) is for braced members and Expression (5.16) is for unbraced members.

In both expressions, the relative flexibilities at either end, $k_1$ and $k_2$, should be calculated. The expression for $k$ given in the Eurocode involves calculating the rotational stiffness of the restraining members making allowance for possible cracking.

Once $k_1$ and $k_2$ have been calculated, the effective length factor, $F$, can be established from Table 4 for braced columns. The effective length is then $l_0 = Fl$.

For a 400 mm square internal column supporting a 250 mm thick flat slab on a 7.5 m grid, the value of $k$ could be 0.11, and therefore $l_0 = 0.59l$. In the edge condition $k$ is effectively doubled and $l_0 = 0.67l$. If the internal column had a notionally ‘pinned’ support at its base then $l_0 = 0.77l$.

In the long term, Expressions (5.15) and (5.16) in the code will be beneficial as they are particularly suitable for incorporation into design software.
Slenderness
Eurocode 2 states that second order effects may be ignored if they are less than 10% of the first order effects. As an alternative, if the slenderness ($\lambda$) is less than the slenderness limit ($\lambda_{\text{lim}}$), then second order effects may be ignored.

Slenderness, $\lambda = \eta / i$ where $\eta = \text{radius of gyration and slenderness limit}$.

$\lambda_{\text{lim}} = \frac{20ABC}{\sqrt{n}} < 15.4C$ where

$A = 1/(1+0.2\varphi_{\text{ef}})$ (if $\varphi_{\text{ef}}$ is not known, $A = 0.7$ may be used)

$B = \sqrt{1+2\omega}$, (if $\omega$, reinforcement ratio, is not known, $B = 1.1$ may be used)

$C = 1.7 - r_m$ (if $r_m$ is not known, $C = 0.7$ may be used – see below)

$n = NEd / (Acf_{\text{cd}})$

$r_m = M_{01}/M_{02}$

$M_{01}, M_{02}$ are the first order end moments, $|M_{02}| \geq |M_{01}|$

If the end moments $M_{01}$ and $M_{02}$ give tension on the same side, $r_m$ should be taken positive.

Of the three factors $A$, $B$ and $C$, $C$ will have the largest impact on $\lambda_{\text{lim}}$ and is the simplest to calculate. An initial assessment of $\lambda_{\text{lim}}$ can therefore be made using the default values for $A$ and $B$, but including a calculation for $C$ (see Figure 6). Care should be taken in determining $C$ because the sign of the moments makes a significant difference. For unbraced members $C$ should always be taken as 0.7.

Column design resistance
For practical purposes the rectangular stress block used for the design of beams (see How to design concrete structures using Eurocode 2: Beams4) may also be used for the design of columns (see Figure 7). However, the maximum compressive strain for concrete classes up to and including C50/60, when the whole section is in pure compression, is 0.00175 (see Figure 8a). When the neutral axis falls outside the section (Figure 8b), the maximum allowable strain is assumed to lie between 0.00175 and 0.0035, and may be obtained by drawing a line from the point of zero strain through the ‘hinge point’ of 0.00175 strain at mid-depth of the section. When the neutral axis lies within the section depth then the maximum compressive strain is 0.0035 (see Figure 8c).
The general relationship is shown in Figure 8d. For concrete classes above C50/60 the principles are the same but the maximum strain values vary.

Two expressions can be derived for the area of steel required, (based on a rectangular stress block, see Figure 8) one for the axial loads and the other for the moments:

\[ A_{SN/2} = \frac{(N_{Ed} - f_{cd} b d_c)}{\left[(\sigma_{sc} - \sigma_{st})\gamma_c\right]} \]

where:
- \( A_{SN/2} \) = Area of reinforcement required to resist axial load
- \( N_{Ed} \) = Axial load
- \( f_{cd} \) = Design value of concrete compressive strength
- \( \sigma_{sc} \) = Stress in compression (and tension) reinforcement
- \( b \) = Breadth of section
- \( \gamma_c \) = Partial factor for concrete (1.5)
- \( d_c \) = Effective depth of concrete in compression
  - \( \lambda \) = 0.8 for \( \leq C50/60 \)
- \( x \) = Depth to neutral axis
- \( h \) = Height of section

\[ A_{SM/2} = \frac{[M - f_{cd} b (h/2 - d_c/2)]}{\left[(h/2 - d_c) (\sigma_{sc} + \sigma_{st})\gamma_c\right]} \]

where:
- \( A_{SM/2} \) = Total area of reinforcement required to resist moment

Realistically, these can only be solved iteratively and therefore either computer software or column design charts (see Figure 9) may be used. A full range of design charts is available from the website www.eurocode2.info.

**Creep**

Depending on the assumptions used in the design, it may be necessary to determine the effective creep ratio \( \phi_{ef} \) (ref. Cl. 3.1.4 & 5.8.4). A nomogram is provided in the Eurocode (Figure 3.1) for which the cement strength class is required; however, at the design stage it often not certain which class applies. Generally, Class R should be assumed. Where the ground granulated blastfurnace slag (ggbs) exceeds 35% of the cement combination or where pulverized fuel ash (pfa) exceeds 20% of the cement combination, Class N may be assumed. Where ggbs exceeds 65% or where pfa exceeds 35%, Class S may be assumed.

**Biaxial bending**

The effects of biaxial bending may be checked using Expression (5.39), which was first developed by Breslaer.

\[ \left( \frac{M_{Edz}}{M_{Rdz}} \right)^a + \left( \frac{M_{Edy}}{M_{Rdy}} \right)^a \leq 1.0 \]

where:
- \( M_{Edz} \) = Design moment in the respective direction including second order effects in a slender column
- \( M_{Rdz} \) = Moment of resistance in the respective direction
- \( a \) = 2 for circular and elliptical sections; refer to Table 5 for rectangular sections
- \( M_{Edy} \) = Total area of reinforcement required to resist bending moment
- \( M_{Rdy} \) = Moment of resistance in the respective direction

\( N_{Rd} = A_{cd} f_{cd} + A_{yd} f_{yd} \)
Unbraced columns

There is no comment made on the design of sway frames in Eurocode 2. However, it gives guidance on the effective length of an unbraced member in Expression (5.16). The value for C of 0.7 should always be used in Expression (5.13N). The design moments should be assessed including second order effects. The tabular method for fire resistance design (Part 1–2) does not explicitly cover unbraced columns.

Walls

When the section length of a vertical element is four times greater than its thickness it is defined as a wall. The design of walls does not differ significantly from that for columns except for the following:

- The requirements for fire resistance (see Table 3).
- Bending will be critical about the weak axis.
- There are different rules for spacing and quantity of reinforcement (see below).


Rules for spacing and quantity of reinforcement

Maximum areas of reinforcement

In Eurocode 2 the maximum nominal reinforcement area for columns and walls outside laps is 4%. However, this area can be increased provided that the concrete can be placed and compacted sufficiently. If required self-compacting concrete may be used for particularly congested situations, where the reinforcing bars should be spaced to ensure that the concrete can flow around them.

Minimum reinforcement requirements

The recommended minimum diameter of longitudinal reinforcement in columns is 12 mm. The minimum area of longitudinal reinforcement in columns is given by:

\[ A_{s,\text{min}} = 0.10 \frac{N_{Ed}}{f_{yd}} \geq 0.002A_c \]

Exp. (9.12N) The diameter of the transverse reinforcement should not be less than 6 mm or one quarter of the maximum diameter of the longitudinal bars.

Note
Spacing requirements for columns
The maximum spacing of transverse reinforcement (i.e. links) in columns (Clause 9.5.3(1)) should not generally exceed:
- 20 times the minimum diameter of the longitudinal bars.
- the lesser dimension of the column.
- 400 mm.
At a distance within the larger dimension of the column above or below a beam or slab these spacings should be multiplied by 0.6.
The minimum clear distance between the bars should be the greater of the 1x bar diameter, aggregate size plus 5 mm or 20 mm.

Particular requirements for walls
The minimum area of longitudinal reinforcement in walls is given by: \( A_{s,min} = 0.002A_c \)
The distance between two adjacent vertical bars should not exceed the lesser of either three times the wall thickness or 400 mm.
The minimum area of horizontal reinforcement in walls is the greater of either 25% of vertical reinforcement or 0.001 \( A_c \). However, where crack control is important, early age thermal and shrinkage effects should be considered explicitly.

Further guidance and advice
- Guides in this series cover: Introduction to Eurocodes, Getting started, Slabs, Beams, Columns, Foundations, Flat slabs and Deflection. For free downloads, details of other publications and more information on Eurocode 2 visit www.eurocode2.info
- This guide is taken from The Concrete Centre’s publication, How to design concrete structures using Eurocode 2 (Ref. CCIP-006)
- For information on all the new Eurocodes visit www.eurocodes.co.uk

References

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