Concrete column design: simplifying Eurocode 2

The analysis of slender columns is a long-standing problem in reinforced concrete design. Methods based on rational theory have been available for steel column design for over a century but reinforced concrete is more difficult: it combines two different materials, one of which has a non-linear stress–strain curve, and there are also shrinkage, creep and cracking to contend with. As a result, theoretical analysis is complicated and tests must be based on long-term loading, making them time-consuming and costly. ***Alasdair N Beal*** *of* ***Thomasons*** *reports.*

Code design rules for concrete columns have tended to rely heavily on the fact that most real reinforced concrete columns are stocky and very slender columns are rare. Code of practice CP 114[1] allowed columns to be designed at full stress up to $L_e/h = 15$, which covered most real columns; above this, the allowable column load was reduced linearly (L_e is the column effective length and h is its overall depth).

Its successor CP 110[2] allowed full stress up to $L_e/h = 12$ and beyond this additional moments were applied to allow for buckling effects. The additional moments were calculated on the assumption that at failure the concrete strain would be at its short-term plastic limit and the steel strain would be at its elastic limit. However, slender column failure is governed by instability, which can occur before the concrete reaches its plastic strain limit. On the other hand, most of the load on real columns is usually long term, so creep can cause strains much greater than short-term values. As a result, despite their increased complexity, agreement between the CP 110 rules and test results was not much better than CP 114. The CP 110 method is still used in its successor, BS 8110[3].

Research

In 1986, the author proposed a new graphical analysis method for slender pin-ended columns, which allows rapid, accurate analysis of non-linear materials such as reinforced concrete under both axial and eccentric loads[4]. This involves preparing a graph of column mid-height deflection against section curvature for various values of slenderness ratio (calculated on the assumption that the column deflected shape follows a sine curve). Another graph is then prepared showing the relationship between curvature and the moment the section can resist at various different values of axial load, with the moment expressed as load eccentricity. When the two graphs are overlaid, it is possible to see the maximum load that a column of any given slenderness ratio can support – and applied load eccentricity and initial imperfections can be allowed for by simply offsetting one graph relative to the other by the appropriate amount. (Having analysed pin-ended columns, the effects of different end conditions etc, can be allowed for by applying appropriate effective length factors in the usual way.)

This method was used to analyse the behaviour of slender columns for both short- and long-term loads over a range of slenderness ratios, load eccentricities, reinforcement ratios and concrete strengths. The results were found to agree well with published test results.

Following publication of this initial paper[4], a comprehensive programme of research, including load tests and detailed analysis of column behaviour, was carried out at Leeds University. This included analysis of the load capacity of pin-ended columns made from normal- and high-strength concrete over a range of slenderness ratios and load eccentricities and with between 0.8 and 4% reinforcement. The effective depth d of column reinforcement in practice is usually in the range 0.8–0.9h, so the analysis was based on $d = 0.8h$. Initial imperfections were allowed for and a creep factor of 2 was assumed for long-term loading on normal-strength concrete (maximum strains were reduced for high-strength concrete). The results were published in a joint paper by Beal and Khalil in 1999[5].

Although this graphical analysis method allows a range of columns to be analysed rapidly once the relevant moment–curvature graphs have been produced, a simpler method is needed for the design of individual columns. Unfortunately, as noted earlier, the behaviour of a reinforced concrete column is too complicated to cover with a simple theoretical formula: the section combines a simple material (steel) with a very complex one (concrete) and at some slenderness ratios the materials are stressed to their plastic limits at failure but at other ratios, capacity is limited by instability and stresses and strains at failure are much lower.

Simple column design methods generally allow for the effects of slenderness on load capacity by either applying reduction factors to the load capacity or else by requiring additional moments to be allowed for in the design. The 1999 Beal/Khalil paper showed that by using additional moments, which have been set to give results which match those from accurate analysis, it is possible to produce design rules which are more accurate than BS 8110 and also simpler to use. The present article shows how the same approach can be used to simplify Eurocode 2.

Eurocode 2

The present Eurocode 2 recommendations are based on research by the Swedish engineer Bo Westerberg, who carried out a detailed computer analysis of slender column behaviour taking into account the relevant effects[6]. Comparison of the results from the Beal – Khalil and Westerberg analyses shows close agreement, as would be expected given that both are based on rigorous theory.

Like BS 8110, the Eurocode 2 design rules[7] allow slenderness effects to be ignored in some situations (Cl. 5.8.3.1(1)) and Cl. 5.8.3.3). However, the calculations that are required limit the value of this simplification. When slenderness effects cannot be ignored, EC2 offers the engineer a choice of three design methods: the 'general method' (Cl. 5.8.6), the 'nominal stiffness method' (Cl. 5.8.7) and the 'nominal curvature method' (Cl. 5.8.8). The 'general' and 'nominal stiffness' methods are rarely used in the UK because of their complexity; engineers generally use the 'nominal curvature' method.

The EC2 'nominal curvature method' superficially appears similar to BS 8110 but it is more complex in practice: first, in addition to calculating the nominal curvature, the engineer must also calculate and add the load eccentricity due to imperfections (Cl. 5.8.8.2(2)). The calculated nominal additional moment is then modified by a correction factor for axial load (Cl. 5.8.8.3(3)) and this in turn is modified for reinforcement arrangement (Cl. 5.8.8.3(2)), creep (Cl. 5.8.3(4)), effective creep ratio (Cl. 5.8.4) and slenderness ratio (Cl. 5.8.3.1). Although this is the simplest column design method offered by EC2, it is still very complicated.

Simplifying EC2

The 1999 Beal – Khalil 1999 paper showed that a simple design method based on 'additional moments' can give reasonably accurate results if the values of these are adjusted empirically to give column capacities, which match the results of an accurate analysis. The recommended additional moment is applied in an ultimate section capacity calculation but the stresses and strains at failure of a slender column may be considerably lower than those assumed in ultimate capacity calculations, so it should be noted that the additional moment used in the design calculation is not necessarily the same as the real moment present at column failure.

Most real columns carry predominantly long-term loads, so the recommendations are based on this. The objective is to produce a set of additional load eccentricities that includes all necessary allowances for initial imperfections, shrinkage and creep and is suitable for the design of columns of all concrete strengths and reinforcement arrangements.

As cracking affects the stiffness of a column, the effect of slenderness on load capacity will vary with the load eccentricity. The Beal – Khalil research found a substantial reduction in capacity between $e = 0$ and $e = 0.1h$ but above this the capacity reduction was more consistent. As most concrete columns carry some moments, the proposed values are based on eccentric loading, so they will be conservative for a column that carries only a concentric load. The comparisons have been based on C32/40 strength-class concrete with either 0.8 or 4% reinforcement, which covers most common structures. C65/80 strength-class concrete has also been considered, to check the effect of varying concrete strength.

The proposed additional load eccentricities for design are shown in Table 1. They are calculated from the formula $e_{add}/h = 0.005L_e/h + 0.00065(L_e/h)^2$. L_e = effective length, h = section overall depth.

Table 1 – Additional load eccentricities for column design

L_e/h	5	10	15	20	25	30	40	50	60
e_{add}/h	0.04	0.12	0.22	0.36	0.53	0.74	1.24	1.9	2.6

Comparison

The graphs in Figures 1–8 show the calculated design capacity (including materials safety factor) of 300 × 300mm columns with various reinforcement proportions and concrete strengths. Results from the proposed design rules (labelled 'proposed') are based on section load/moment capacities calculated with Concrete Centre spreadsheet TCC52. These are compared with the Beal–Khalil published accurate analysis results[5] (labelled 'theory') and also with results from the current EC2 'nominal curvature method' (labelled 'EC2'), which have been calculated using commercial software (TEDDS).

Figures 1 and 2 show results for an axially loaded C32/40 300 × 300mm column with 0.8% or 4% steel. As can be seen, the proposed design rules give conservative results; existing EC2 design rules are unconservative for L_e/h between 5 and 20 and also for 4% steel. Figures 3 and 4 show the results for 0.8% reinforcement and load eccentricities of $0.1h$ and $0.5h$; Figures 5

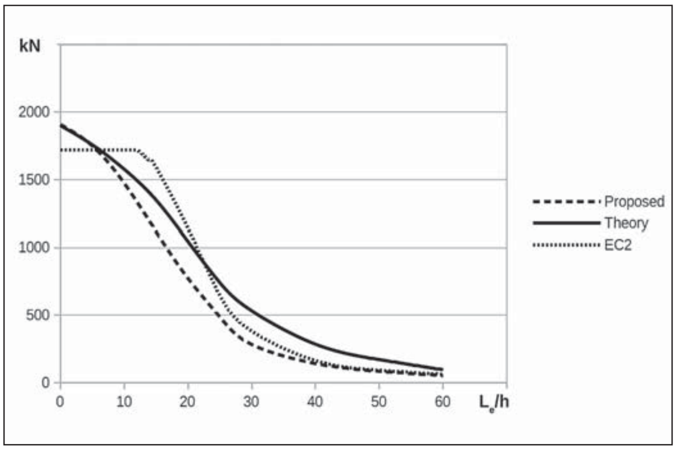

Figure 1: C32/40, 0.8% steel, $e = 0$.

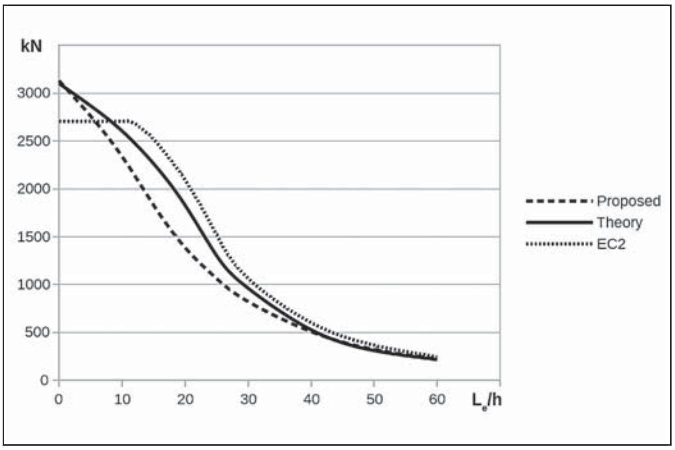

Figure 2: C32/40, 4% steel, $e = 0$.

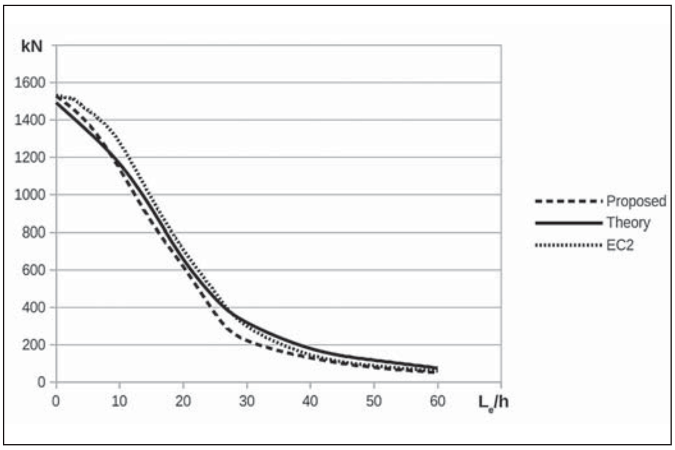

Figure 3: C32/40, 0.8% steel, $e = 0.1h$.

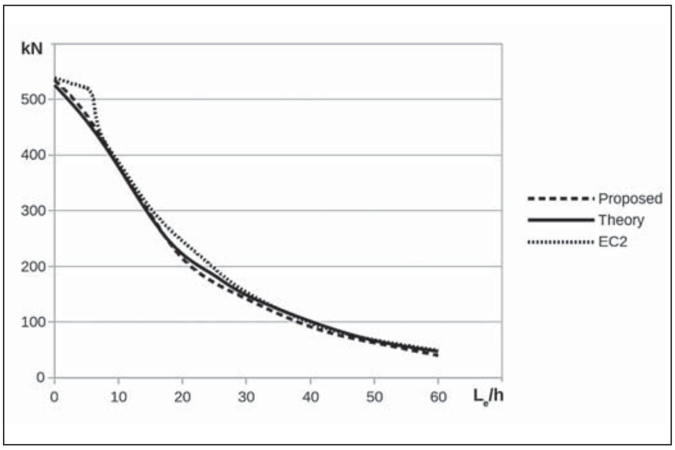

Figure 4: C32/40, 0.8% steel, $e = 0.5h$.

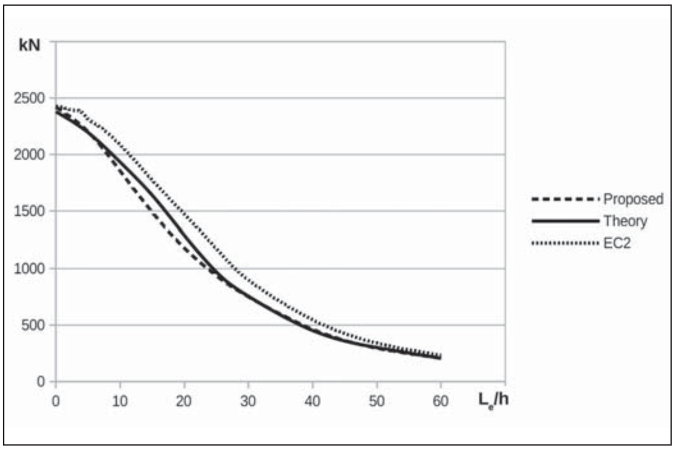

Figure 5: C32/40, 4% steel, $e = 0.1h$.

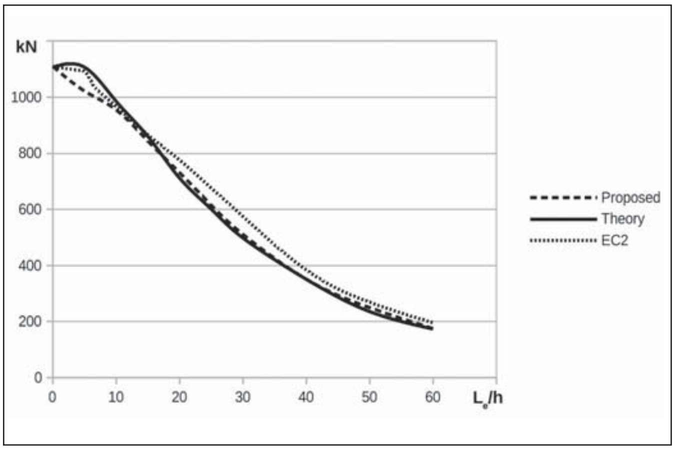

Figure 6: C32/40, 4% steel, $e = 0.5h$.

and 6 show the corresponding results for 4% reinforcement. As can be seen, the proposed new rules and the existing EC2 design rules both agree closely with the results from the accurate analysis: the proposed new rules are generally slightly conservative, whereas the EC2 rules are slightly unconservative for 4% steel and at low values of L_e/h. For load eccentricities $0.1h$, $0.3h$ and $0.5h$, the average capacity (proposed/theory) is 0.95, with a minimum of 0.67 and maximum of 1.06; in the important range L_e/h 5–20, the average capacity (proposed/theory) is 0.98, with a minimum of 0.91 and maximum 1.03.

Figures 7 and 8 show the results for a C65/80 column with 0.8% steel respectively and 4% steel and applied load eccentricity $e = 0.1h$. Again, the results agree closely with the accurate theoretical analysis and comparisons for higher load eccentricities up to $e = 0.5h$ give similar results. For load eccentricities $0.1h$, $0.3h$ and $0.5h$, the average capacity (proposed/theory) is 0.90, with a minimum of 0.47 and maximum of 1.08; in the important range L_e/h 5–20, the average capacity (proposed/theory) is 0.94, with a minimum of 0.82 and maximum of 1.07.

Therefore the proposed additional load eccentricities are suitable for design of all columns with between 0.8 and 4% reinforcement and for all concrete strengths up to C65/80.

Proposed amendments to EC2

The following clause may either be inserted as a replacement for the present Cl. 5.8.8 'Method based on nominal curvature' or as a possible alternative design method.

Simple 'additional moment' design method for columns

1. In this method, an additional moment to allow for imperfections and slenderness effects is added to the first-order design moment and the section is then designed for the axial force and the total bending moment in accordance with 6.1. The specified additional eccentricities include an allowance for initial imperfections, so

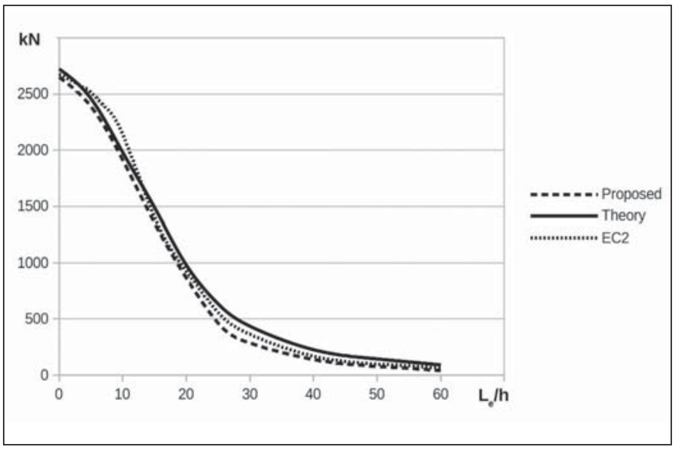

Figure 7: C65/80, 0.8% steel, $e = 0.1h$.

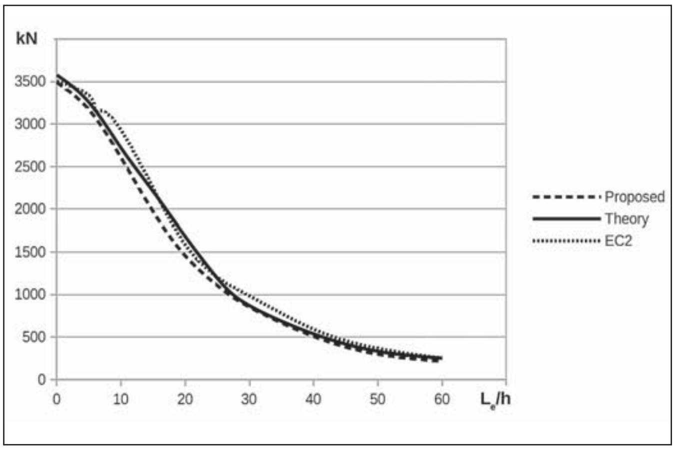

Figure 8: C65/80, 4% steel, $e = 0.1h$.

Table 2 – Simple 'additional moment' design method: additional load eccentricity e_{add}

L_e/h	5	10	15	20	25	30	40	50	60
e_{add}/h	0.04	0.12	0.22	0.36	0.53	0.74	1.24	1.9	2.6

$e_{add}/h = 0.005L_e/h + 0.00065(L_e/h)^2$

where L_e = effective length, h = overall section depth in direction of buckling

in this design method, imperfections do not need to be added to the first-order moment.

2. The design moment is:
$M_{Ed} = (M_{0Ed} + M_{add})$, or M_{02}, whichever is greater, where:
   - M_{0Ed} is the first-order moment (see item 3 below)
   - $M_{add} = N_{Ed}\, e_{add}$
   - e_{add} is an additional load eccentricity to allow for buckling effects and imperfections (see item 4 below)
   - M_{02} is the larger end moment.
3. If the column is unbraced, M_{0Ed} is the maximum first-order moment anywhere in its length. If the column is braced, M_{0Ed} = maximum first-order moment between 0.4L and 0.6L.
4. The additional eccentricity e_{add} to allow for the effects of slenderness and imperfections is shown in Table 2. Intermediate values may be interpolated. ■

Acknowledgements:

Thanks are due to James Massey for assistance with the calculations and to Charles Goodchild and Paul Gregory at The Concrete Centre for assistance with interpretation of some points in EC2.

References:

1. BRITISH STANDARDS INSTITUTION, CP 114. *The structural use of reinforced concrete in buildings*. BSI, London, 1969.
2. BRITISH STANDARDS INSTITUTION, CP 110. *Code of practice for the structural use of concrete. Part 1 – design, materials and workmanship*. BSI, London, 1972.
3. BRITISH STANDARDS INSTITUTION, BS 8110. *Structural use of concrete. Part 1 – Code of practice for design and construction*. BSI, London, 1985.
4. BEAL, A.N. The design of slender columns. *Proceedings of the Institution of Civil Engineers Part 2*, Vol. 81, September 1986, pp.397–414, available at:
5. BEAL, A.N. and KHALIL, N. Design of normal- and high-strength concrete columns. *Proceedings of the Institution of Civil Engineers: Structures and Buildings*, Vol. 134, November 1999, pp.345–357, available at: *www.anbeal.co.uk*.
6. WESTERBERG, B. *Second order effects in slender concrete structures*. KTH (Royal Institute of Technology in Stockholm), Civil and Architectural Engineering, Department of Concrete Structures, Report 77, 2004.
7. BRITISH STANDARDS INSTITUTION, BS EN 1992-1-1. *Eurocode 2: Design of concrete structures. Part 1-1 – General rules and rules for buildings*. BSI, London, 2004, revised 2008.