Design of Angles

David Brown of the SCI offers advice on the use of angles in bending, in response to questions received by the advisory service. Angles subject to bending are often found carrying loads over openings, but also may be found as continuous chords in trusses. Eurocode guidance follows that presented in the previous standard, BS 5950.

Using an angle in bending? Select another profile!

Questions relating to angle sections are surprisingly common at the SCI. Usually, they are not related to the use of angles in compression (typically in a truss) where the design guidance is clear, but rather concern the bending resistance of angles. Often, it becomes clear that the angle is unrestrained, so the real issue is the buckling resistance of the member. In those situations, the SCI's advice is to select a different profile. Angles in bending are often used to support brickwork over openings. Although this is a common detail in domestic applications, the member selection is fraught with potential risk. As illustrated in Figure 1, the compressed leg will wish to move out of plane, which combined with the usual eccentric application of load will lead to a twist of the member – and a dissatisfied client if the supported façade cracks.

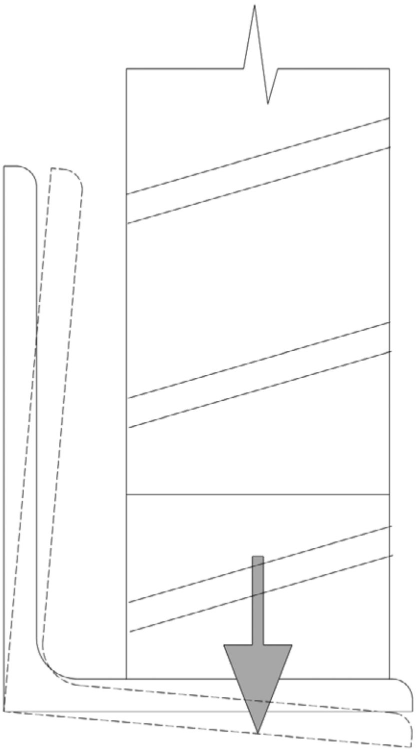

Figure 1: Behaviour of a single angle under load

As an aside to the main theme of this article, any member supporting an eccentric load will twist. When carrying eccentric loads commonly found in domestic construction (but equally applicable in all situations) thought should be given to using a hollow section which is torsionally very stiff. Although the hollow section member itself may be more expensive and the connections more involved, the risk of twist has been minimised. Figure 2 shows a member to be used in a house extension – a selection commended by the author.

Angles in compression

Here, the design guidance is straightforward. Angles do not buckle about their rectangular axes which are aligned with the angle legs, but buckle about their principal axes, u-u or v-v, as shown in Figure 3.

Figure 2: Torsionally stiff member for eccentric loading condition

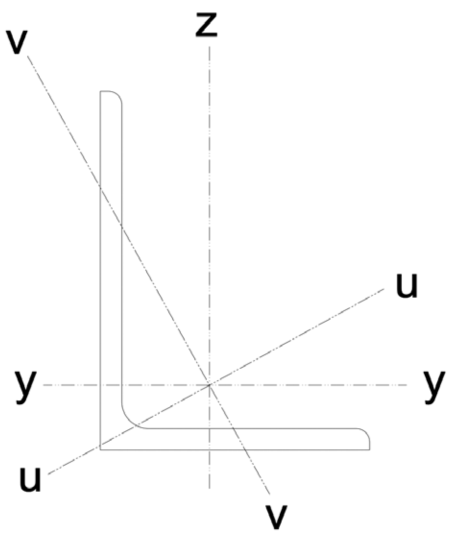

Figure 3: Axis identification for angles

Following the same principle as illustrated in Figure 1, each leg wishes to buckle in its own out-of-plane direction, which causes a twist. This torsional behaviour is allowed for in the calculation of the slenderness, which considers the different axes, adjusts the slenderness for the torsional behaviour and finally allows for the restraint (or otherwise) offered by the end connections. The determination of slenderness is covered in clause 4.7.10 in BS 5950. Section BB.1.2 of BS EN 1993-1-1 provides equivalent (but not as comprehensive) guidance.

▸28

▸26

Angles in bending – lateral torsional buckling

BS 5950 looks hopeful, since clause 4.3.8 covers the buckling resistance moment for single angles and provides both a basic method and a simplified method. Optimism may be misguided, especially if unequal angles have been selected. As will be seen later, the designer must overcome a number of challenges.

Equal angle buckling resistance moment – BS 5950 simplified method

Assuming that the angle is being used to carry load across an opening, the heel of the angle is in tension. The simplified method of BS 5950 clause 4.3.8.3 gives the buckling resistance moment, M_b for members subject to bending about the x-x axis as:

$$M_b = p_y Z_x \left(\frac{1350\varepsilon - L_E/r_v}{1625\varepsilon}\right) \text{ but } M_b \leq 0.8\, p_y Z_x$$

Where $\varepsilon = (275/p_y)^{0.5}$

BS 5950 specifies the elastic modulus is to be used in the calculations.

Assuming the angle is 150 × 150 × 12, 4 m long and S275, then ε = 1.0 and (from section tables) r_v = 29.5 mm.

$$\text{Then } M_b = 275 \times 67.7 \times 10^3 \left(\frac{1350 \times 1 \times 4000/29.5}{1625 \times 1}\right) \times 10^{-6} = 13.9\text{kNm}$$

Equal angle buckling resistance moment – BS EN 1993-1-1

The Eurocode is less helpful, as no design advice is given. Designers are encouraged to consult The Institution of Structural Engineers' "Grey Book"[1] which recommends that the applied moment be resolved about the u-u and v-v axes, and an interaction expression used to verify the member. The relative slenderness $\bar{\lambda}_{LT}$ is given by:

$$\bar{\lambda}_{LT} = 0.72 v_a \sqrt{\frac{f_y}{E}}\, \phi_a \lambda_v$$

This is a rearrangement of the expression given for λ_{LT} in B.2.9.2 of BS 5950, determined by dividing the BS 5950 slenderness by $\lambda_1 = \pi\sqrt{\frac{E}{f_y}}$.

ϕ_a is the equivalent slenderness coefficient and is given in the "Blue Book" as 3.77 for this particular angle.

The value of v_a is more complicated, and is given by:

$$v_a = \frac{1}{\sqrt{\sqrt{\left(1+\left(\frac{4.5\psi_a}{\lambda_v}\right)^2\right)}+\frac{4.5\psi_a}{\lambda_v}}}$$

This is the same presentation as found in B.2.9.3 of BS 5950.

ψ_a is the monosymmetry index, found in the Blue Book for unequal angles. For equal angles, ψ_a = 1.

For the selected angle, $\lambda_v = {}^{4000}/_{29.5} = 135.6$

$$v_a = \frac{1}{\sqrt{\sqrt{\left(1+\left(\frac{4.5 \times 1}{135.6}\right)^2\right)}+\frac{4.5 \times 1}{135.6}}} = 0.984$$

Therefore:

$$\bar{\lambda}_{LT} = 0.72 \times 0.984 \times \sqrt{\frac{275}{21000}} \times 3.77 \times 135.6 = 0.580$$

From Table 6.4 of BS EN 1993-1-1, curve d must be selected, and α_{LT} = 0.76 from Table 6.3.

According to expression (6.56), χ_{LT} = 0.724

In the "Grey Book", the applied moment is resolved into moments about the u-u and v-v axes and the buckling resistance moment calculated about the u-u axis. The moment resistance about the v-v axis is the resistance of the cross section. Using the elastic modulus about the u-u axis poses an immediate problem as this property is not given in published tables. The second moment of area about the u-u axis is given as 1170 cm^4 and the dimension c to the centroid given as 41.2 mm. The distance to the extreme fibre at the angle toe is 106 mm. The minimum modulus, W_u is given by:

$$W_u = \frac{1170 \times 10^4}{106} = 110 \times 10^3\text{mm}^3$$

The modulus about the v-v axis can be calculated as

$$\frac{303 \times 10^4}{58.3} = 52 \times 10^3\text{mm}^3$$

The lateral torsional buckling resistance is then given by:

$$M_b = \frac{0.724 \times 275 \times 110 \times 10^3}{1.0} \times 10^{-6} = 21.9 \text{ kNm}$$

This is the LTB resistance about the u-u axis, so cannot be compared directly with the buckling moment calculated according to BS 5950.

If the applied moment was 14 kNm in the major axis, the resolved moments in the u-u and v-v axes are both 9.9 kNm

According to the "Grey Book", the interaction to be satisfied is:

$$\frac{M_{v,Ed}\gamma_{M0}}{W_v f_y} + \frac{M_{u,Ed}\gamma_{M1}}{\chi_{LT} W_{el,u,min} f_y} \le 1.0$$

Substituting:

$$\frac{9.9\times10^6\times1.0}{52\times10^3\times275} = \frac{9.9\times10^6\times1}{21.9\times10^6} \le 1.14$$ which is unsatisfactory.

The approach set out in the "Grey Book" is following the advice given in clause I.4.2 of BS 5950, described as the "Basic Method", which requires the applied moments to be resolved about the principal axes u-u and v-v, and an interaction check for biaxial moments to be completed. BS 5950 refers the designer to clause 4.8.3.3.1 for the biaxial check, but using the moments and resistances about the principal axes in the same way as the "Grey Book". The only notable difference is that the LTB resistance according to BS 5950 is 26 kNm, compared to the value of 21.9 kNm computed above. According to BS 5950, the interaction result is 1.07, lower than the Eurocode result, due solely to the increased LTB resistance.

The "Simplified method" of I.4.3 uses the "Simplified method" of clause 4.3.8.3 to calculate the buckling resistance moment, M_b about the x-x axis. This value is then used in the interaction expression of I.4.3, but using the moments and resistances about the rectangular axes. With an applied moment of 14 kNm about the major axis only and a resistance $M_{bx} = M_b = 13.9$ kNm as calculated above, the interaction result is 1.01.

Buckling of unequal angles – more complexity

BS 5950 does not permit the "Simplified method" to be used for unequal angles – the "Basic method" of clause 4.3.8.2 must be used. This is going to be painful for designers, as an unequal angle is probably preferable – at least by intuition, to have the longer leg vertical if spanning over an opening. In Both BS 5950 and the "Grey Book", applied moments are to be resolved into the u-u and v-v axes. The position of the centroid and the angle between the principal axes and the rectangular axis is given in the Blue Book, so this is not overly difficult. The Blue Book also gives the second moment of area about the u-u and v-v axes, so with some trigonometry, the distances to the extreme fibres and the modulus about each principal axis can be determined. The monosymmetry index is given, so the calculation of v_a given above can be completed.

The complexity is not over, especially if the angle is not at least Class 3 (semi-compact in BS 5950). According to Table 11 of BS 5950, the Class 3 limit for a single angle when the compression is due to bending is 15ε, so a 150 × 10 leg in S275 would be satisfactory, but nothing more slender. According to BS EN 1993-1-1 and Table 5.2, the limiting value is 14ε, but based on the dimension c. For a 150 × 10 leg, the dimension c is around 128 mm, so c/t = 12.8 and the limiting value is 12.9, meaning the same conclusion is reached.

If the angle is Class 4 (and many are), the Eurocode method of calculating effective properties, or the BS 5950 alternative of using a reduced design strength adds more complexity. If the member is used under combined bending and axial (for example, as a continuous chord in a truss), the design effort involved with a Class 4 angle is likely to be too much to be worthwhile.

Conclusions

This article has identified two messages. Firstly and most importantly, an angle may be cost-effective but is not suitable for carrying significant moments. Under bending, and under axial loads, there is torsional behaviour causing a significant twist, which may be very detrimental if an angle is supporting brittle materials. The second message is that the verification of an unequal angle in bending is complicated – more so if the member is Class 4 and even more so if the member is subject to combined axial load and bending. If faced with this design situation, an equal angle of at least Class 3 cross section is recommended. In general, the author's advice remains that if faced with an angle subject to unrestrained bending, substituting an alternative profile is a much better solution. ■

1. Manual for the design of steelwork building structures to Eurocode 3: October 2010 ISE, 2010