The design of tee sections in bending

David Brown of the SCI looks at the lateral torsional buckling resistance of tee sections, considering the rules in BS 5950 and BS EN 1993-1-1

A tee section? In bending?

A tee section seems an unlikely choice for a member in bending, but judging by the calls to SCI's Advisory Desk, designers do wish (or are perhaps required) to use them. Normally, a tee might be used as a tie between floor beams. The vertical web fits between floor units and the flange sits just below the units, making little impact on an uninterrupted soffit. Before hollow section trusses became popular, tees would have been a good choice for the chords of roof trusses. The web of the tee (if cut from a UB section) provides enough room to connect the angle internal members, either by bolting or welding.

This article considers the alternative ways to design a tee section in both BS 5950 and BS EN 1993-1-1, illustrated with a worked example, so that designers have a resource if faced with the challenge of an unrestrained tee in bending.

BS 5950 guidance

The verification of a tee is covered in Section B.2.8, which provides rules to calculate the equivalent slenderness for lateral torsional buckling (LTB). The first point to note is that guidance is given on when LTB should be considered, and when not. To avoid confusion with Eurocode terminology, the axis on the web centreline will be referred to as the minor axis and the perpendicular axis, the major axis.

In B.2.8.2 a), the Standard advises that if $I_{major} = I_{minor}$ LTB does not occur and λ_{LT} is zero. The same applies to doubly-symmetrical sections where there is no reason for the section to buckle in the minor axis.

The reverse is true for tees cut from a UB – major axis inertia is larger than the minor axis inertia and LTB is possible.

Part b) of the clause notes that "if $I_{minor} > I_{major}$ LTB occurs about the major axis and λ_{LT} is given by:

$$\lambda_{LT} = 2.8\left(\frac{\beta_w L_e B}{T^2}\right)^{0.5}\text{''}$$

where B is the flange breadth and T is the flange thickness. Many tees will fall into this category – notably those cut from UC sections where the web is short and the flange is wide and thick. A simply supported tee section with $I_{minor} > I_{major}$, loaded so as to put a short unrestrained stem in compression will buckle by twisting to reduce the compression in the stem.

This clause may lead to some significant confusion, because the expression for λ_{LT} for a tee is the same as the equivalent expression for a plate bent about its major axis, given in clause B.2.7. The expression is based on the St Venant torsional stiffness of the flange only; the stem of the tee and any warping stiffness are ignored, hence the similarity with the expression for buckling of a flat plate.

Finally, part c) of the clause describes when $I_{major} > I_{minor}$ (the common situation for tees cut from UB) and provides the familiar (for designers of a certain age!) expression:

$$\lambda_{LT} = uv\lambda\sqrt{\beta_w}$$

The clause goes on to provide expressions for the relevant section properties needed to evaluate λ_{LT}, but designers will mostly obtain these from section property tables. In this case, the warping stiffness of the section is included in the determination of λ_{LT}.

BS EN 1993-1-1 guidance

For tees, there is no change from the normal procedure. To calculate the non-dimensional slenderness $\bar{\lambda}_{LT}$ the elastic critical buckling moment, M_{cr} is needed. This challenge is conveniently addressed by using software.

Verification methods

In the particular example chosen, the tee is cut from a UB, and thus has a relatively long web. Classification to either Standard leads to the conclusion that the tee is slender (BS 5950) or class 4 (BS EN 1993-1-1).

Two approaches are then possible in both Standards. Either the design stress can be reduced until the section becomes Semi-compact/Class 3, or an effective section can be determined by neglecting the ineffective parts of the cross-section. This latter approach becomes more involved in the Eurocode, because the effective section depends on the stress ratio in the web, which depends on the position of the neutral axis, which moves as the effective section reduces – so an iterative process is needed. BS 5950 is more straightforward as uniform stress in the web is assumed.

Worked example

The tee is a 152 × 229 × 30, in S355, with a buckling length of 4 m. The applied moment is in the plane of the web about the major axis and the web is in compression. The section is shown in Figure 1.

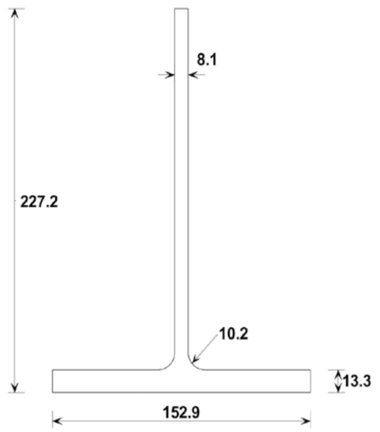

Figure 1: Tee section dimensions

Method 1 – BS 5950 reduced design stress

From look-up tables, d/t for the web = 28

From Table 11, the Class 3 limit is 18ε, and as $\varepsilon = 0.88$, the limit is 15.84. The section is therefore slender.

Clause 3.6.5 allows the use of a reduced design stress, p_{yr} given by:

$$p_{yr} = \left(\frac{15.84}{28}\right)^2 \times 355 = 114\ \text{N/mm}^2$$

Various section properties are needed from section tables:

minor axis radius of gyration, r_{yy} = 32.3 mm

buckling parameter, u = 0.648

monosymmetry index, ψ = -0.746 (negative as the flange is in tension)

▶28

▶26 elastic modulus, $Z = 111$ cm^3
plastic modulus, $S = 199$ cm^3
With some careful spreadsheet work:
$v = 1.05$
$w = 0.00449$ (includes the warping constant)
$\beta_w = 111/199 = 0.558$
$\lambda = 4000/32.3 = 123.8$
Then $\lambda_{LT} = 0.648 \times 1.05 \times 123.8 \times \sqrt{0.558} = 62.9$
The bending strength can then be calculated from B.2.1, with the result that
$p_b = 105$ N/mm^2
The buckling resistance moment $M_b = 105 \times 111 \times 10^{-3} = 11.7$ kNm

Method 2 – BS 5950 effective section method

Given that the section is slender, an effective section may be calculated. Clause 3.6.2.2 prescribes that the effective width of a class 4 slender outstand should be taken as equal to the class 3 limiting value (18ε, as above).

The overall depth of the effective section is therefore $18 \times 0.88 \times 8.1 = 128.3$ mm. The dimensions of the effective section are shown in Figure 2.

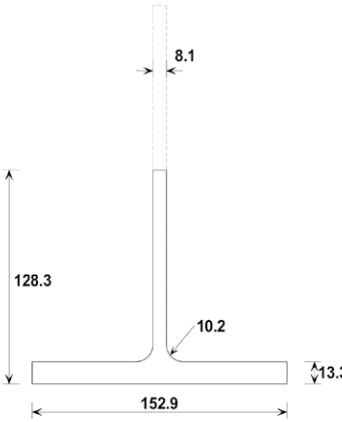

Figure 2: BS 5950 effective section

Calculations are required to determine the position of the neutral axis (accounting for the root radii if doing a 'proper' job!), and calculating the effective elastic modulus of the section. The effective elastic modulus is calculated as 36.3 cm^3.

$$\beta_w = \frac{36.3}{199} = 0.18$$

Then $\lambda_{LT} = 0.648 \times 1.05 \times 123.8 \times \sqrt{0.18} = 35.7$
Following the same process from B.2.1, the bending strength,
$p_b = 339$ N/mm^2
The buckling resistance moment $M_b = 339 \times 36.3 \times 10^{-3} = 12.3$ kNm

Method 3 – BS EN reduced stress method

The ratio for local buckling is defined differently in the Eurocode, which species c/t as the dimensions of the outstand, not overall depth.

$$c/t = \frac{(227.2 - 13.3 - 10.2)}{8.1} = 25.2$$

The limiting value depends on the stress ratio between the stress at the tip of the web, and at the root radius (refer to Table 5.2 in BS EN 1993-1-1). To evaluate the limit, BS EN 1993-1-5 must be consulted to calculate the buckling factor, k_σ.

If the neutral axis is at 58.4 mm from the face of the flange (from section property tables), the stress ratio may be calculated from the dimensions shown in Figure 3.

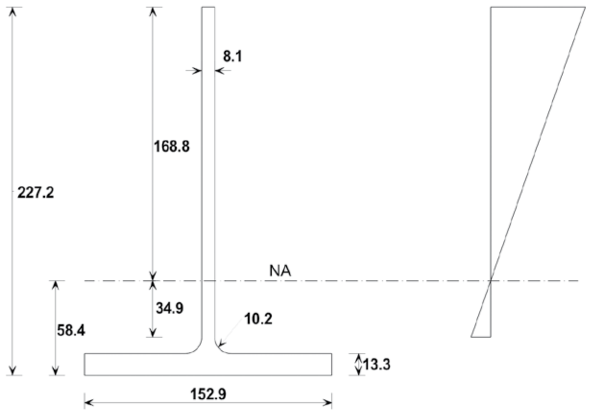

Figure 3: Elastic stresses in the web of the gross section

$$\psi = \frac{-34.9}{168.8} = -0.207$$

From Table 4.2 of BS EN 1993-1-5, then
$k_\sigma = 0.57 - 0.21\psi + 0.07\psi^2$
$k_\sigma = 0.57 - 0.21 \times (-0.207) + 0.07 \times (-0.207)^2 = 0.616$
Back in BS EN 1993-1-1 Table 5.2,
the limit is $21\sqrt{k_\sigma} = 21 \times 0.81 \times \sqrt{0.616} = 13.3$
25.2 > 13.3, so the section is class 4 (not surprisingly, given the BS 5950 classification)
To ensure the section remains class 3, the reduced design strength is given by $235 \Big/ \left(\frac{25.2}{21 \times \sqrt{0.616}}\right)^2 = 100.5$ N/mm^2

M_{cr} must be calculated, using the gross properties. *Ltbeam* is a convenient software to use. With a UDL causing compression on the web, M_{cr} = 67 kNm.

Verification then proceeds in the usual way, using the general case of clause 6.3.2.2. A tee section is taken to be an "other cross section" in Table 6.4. The intermediate values are therefore:

$\bar{\lambda}_{LT} = 0.41$
$\alpha_{LT} = 0.76$
$\varphi_{LT} = 0.66$
$\chi_{LT} = 0.84$
and finally M_{bRd} = 9.5 kNm

Method 4 – BS EN effective section method

Having found the section is class 4, the effective length of the web may be determined from BS EN 1993-1-5.

If $k_\sigma = 0.616$ then from clause 4.4(2)

$$\bar{\lambda}_p = \frac{\bar{b}/t}{28.4\varepsilon\sqrt{k_\sigma}} = \frac{25.2}{28.4 \times 0.81 \times \sqrt{0.616}} = 1.39$$

Because $\bar{\lambda}_p > 0.748$ then

$$\rho = \frac{\bar{\lambda}_p - 0.188}{\bar{\lambda}_p^{\,2}} = \frac{1.39 - 0.188}{1.39^2} = 0.622$$

The effective length of the web from the neutral axis is therefore 0.622 × 168.8 = 105 mm and the overall depth of the effective section is now 163.7 mm.

This change of section means that the original assumptions about *c/t* ratio, position of neutral axis etc are now invalid. The process must be repeated (by spreadsheet preferably!) until a final solution is found. A final solution is found when there is no further reduction needed to the web (i.e. all the reduced section is effective). This happens when $\rho = 1$ (no reduction), which, with reference to BS EN 1993-1-5, happens when $\bar{\lambda}_p = 0.748$

Probably, there would be a neat way to determine this point by calculation, but it is easy to complete a number of cycles to discover the point when the entire reduced section becomes effective. The final section, with an overall depth of 130 mm, is shown in Figure 4. The Eurocode effective section appears reassuringly similar to that according to BS 5950, in Figure 2.

Having found the final section, the section properties can be determined and the resistance determined in the normal way, as Method 3. The intermediate values are:

$W_{el} = 37.3\ \text{cm}^3$
$\bar{\lambda}_{LT} = 0.44$
$\alpha_{LT} = 0.76$
$\varphi_{LT} = 0.69$

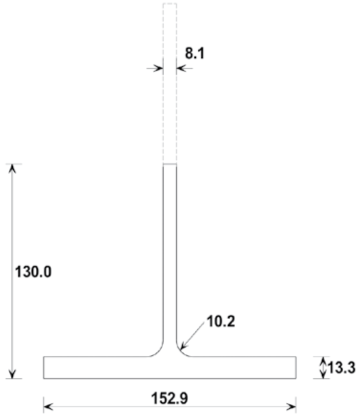

Figure 4: EN 1993 effective section

$\chi_{LT} = 0.82$
and finally M_{bRd} = 10.8 kNm

Summary

The various resistances are shown below:

BS 5950 reduced design strength	11.3 kNm
BS 5950 effective section	12.3 kNm
BS EN 1993-1-1 reduced design strength	9.5 kNm
BS EN 1993-1-1 effective section	10.8 kNm

Note that according to BS 5950, the maximum moment should be limited to M_b/m_{LT}, so the BS 5950 values above should be increased by $1/0.925$ to provide a proper comparison. The shape of the bending moment diagram – due to a UDL – is already included in the Eurocode resistances by virtue of the M_{cr} value.

Conclusions

Firstly, it is not easy to calculate the correct resistance. It took some time and the assistance of two colleagues at SCI to reach a consensus. The Eurocode approach has the benefit of software to calculate M_{cr}, but the easier solution (method 3, reduced design strength) is conservative. The less conservative method 4, effective section, is painful because of the loops required to calculate the effective section.

The second observation is that perhaps the guidance in BS 5950 could be clearer.

The final observation is that tees have their place - but preferably not as unrestrained members in bending.