Design of steel beams with large web openings

BS EN 1993-1-13: Beams with large web openings has been published by BSI. It deals with the design of steel beams with circular, hexagonal, rectangular, elongated circular and sinusoidal openings and is a sister-document to the design of composite beams with large web openings that is being worked on currently under EN 1994-1-1. Mark Lawson of the SCI, who was a member of the Project Team, explains some of the technical aspects of this new Part.

To a UK audience, Eurocode 3 Part 1–13 *Beams with Large Web Openings* follows the SCI publication P-355 relatively closely and it includes the following information:

- Application for steel grades up to S460.
- Rules for different opening shapes.
- Beams with relative slender webs depths, $h_w \leq 121\ t_w\ \varepsilon$, where t_w is the web thickness.
- Limits on web opening sizes for both unstiffened and stiffened openings.
- Two methods for Vierendeel bending checks at circular openings, which are a simplified equivalent rectangle method and a radial stress method.
- Web-post buckling rules, now using buckling curve 'a' to BS EN 1993-1-1 and extended to include hexagonal openings.
- Rules for the buckling resistance of the compressed top Tee at long openings.
- Rules for end-post buckling based on an adaptation of the web-post buckling rules.
- Rules for asymmetric steel sections taking account of an in-plane web-post moment required for re-distribution of shear forces between the Tees.
- Simplified rules for the additional deflection due to large web-openings.
- Lateral torsional buckling verifications based on the section properties at the centre-line of the openings.

This article covers the principles of design of large web openings in steel beams and a second article will summarise the rules for end-posts based on recent tests at City, University of London.

The limits on maximum opening sizes for unstiffened openings are presented in Table 1, below. These are Nationally Determined Parameters so could be modified for use in the UK. In this table, the effective opening length of elongated circular openings is taken as $a_{eff} = a_o - 0.3h_o$, where a_o is the opening length. The corresponding limiting dimensions for longitudinally stiffened openings are given in a further table.

Verifications at large web openings

The verifications that should be made at large web openings in steel beams are:

- Pure shear check based on the reduced depth of the web
- Bending resistance at the centre-line of the opening
- Vierendeel bending of the web-flange Tees due to transfer of shear across the opening
- Web buckling next to isolated openings
- Web-post shear and buckling between closely spaced openings
- End-post shear and buckling next to the connections
- Combined compression and bending of slender top Tees in regions of high moment
- Calculations of the relative deflection across large web openings, where this impairs the serviceability performannce

The resistance to Vierendeel bending of the Tees at large rectangular openings can be increased by welding horizontal stiffeners on one or both sides of the beam that project at least 150mm past the ends of the opening to act as an 'anchorage length'.

For Vierendeel bending at circular, elongated circular and hexagonal openings, the equivalent rectangular opening width, a_{eq}, defines the double curvature moment that is developed in the web-flange Tees. The critical angle for Vierendeel bending around a circular opening is at approximately 26° to the vertical and so the equivalent rectangular opening width for this verification is given as $a_{eq} = 0.45\ h_o$, where h_o is the opening diameter.

Web-post buckling between openings

For closely spaced openings, web-post buckling may occur due to the transfer of horizontal shear which leads to 'strut and tie' action in the web-post. The method for web -post buckling uses an effective length of the equivalent strut, which is illustrated in Figure 1 (over page) for adjacent circular openings. The buckling strength is obtained using buckling curve 'a' to EN 1993-1-1, which is justified by correlation with tests and by the additional restraints to plate buckling in comparison to an equivalent strut.

For this verification, the compressive force acting on the web-post, $N_{wp,Ed}$ should be taken equal to the horizontal shear force in the web-post and it is required that the buckling resistance of the web-post exceeds this force.

The non-dimensional slenderness of the web-post is defined as follows for ▸26

Table 1 : Limiting dimensions for different shapes of unstiffened openings

Shape of opening	Maximum opening height, h_o	Maximum opening length, a_o	Minimum edge to edge spacing, s_o	Minimum depth of Tee	
				Tee in compression	Tee in tension
Circular	0.8 h	-	0.1 h_o	Max($t_f + r$ + 10mm; t_f +30mm)	Max($t_f + r$ + 10mm; t_f +30mm)
Hexagonal	0.75 h	1.5 h_o	0.25 h_o		
Rectangular	0.75 h	2.5 h_o	Max(0.5a_o;h_o)	Max(a_o / 12; 0.1h)	0.1h
Elongated	0.8 h	3 h_o	Max(0.25a_{eff};0.5h_o)	a_{eff} / 12	Max($t_f + r$ + 10mm; t_f +30mm)
Sinusoidal	0.8 h	5 h_o	0.25 h_o	a_{eff} / 12	

a_{eff} = effective opening length; h = beam depth; t_f = flange thickness; r = root radius

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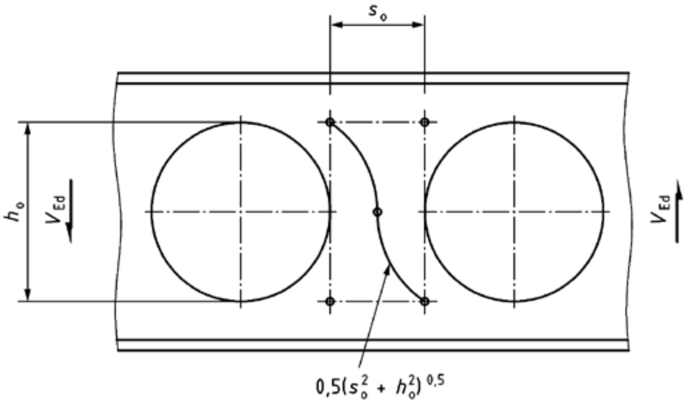

Figure 1 - Illustration of the effective length due to web-post buckling between circular openings

the different opening shapes, where so is the edge to edge spacing of the openings.

For circular openings and elongated circular openings:

$$\bar{\lambda}_{wp} = \frac{1.75\sqrt{s_0{}^2 + h_0{}^2}}{t_w}\frac{1}{\lambda_1} \text{ but } \bar{\lambda}_{wp} \leq \frac{2.4\, h_0{}^2}{t_w}\frac{1}{\lambda_1}$$

For cellular beams with unequal web thickness in the two parts, t_w may be taken as the average web thickness in this formula.

For rectangular openings:

$$\bar{\lambda}_{wp} = \frac{2.5\sqrt{s_0{}^2 + h_0{}^2}}{t_w}\frac{1}{\lambda_1} \text{ but } \bar{\lambda}_{wp} \leq \frac{3.5\, h_0{}^2}{t_w}\frac{1}{\lambda_1}$$

The web-post buckling resistance should be taken as:

$N_{wp,Rd} = \chi_{wp}\, s_o \min\{t_{w,tT} f_{y,tT}\,;\, t_{w,bT} f_{y,bT}\} / \gamma_{M1}$

Where χ_{wp} is determined to buckling curve 'a' using λ_{wp}

$t_{w,tT} f_{y,tT}$ and $t_{w,bT} f_{y,bT}$ are the multiples of the top or bottom web thickness and the steel strengths for these parts.

γ_{M1} is taken as 1.0.

Buckling Resistance of a Compressed Top Tee at a Large Rectangular Opening

A new method is presented for the stability of slender Tees at long web openings. The definition of a 'long opening' is given in clause 8.3.2 (1). The combination of compression, Vierendeel bending and bending from local applied loads acting on a slender is determined as follows:

$$\frac{N_{T,Ed}}{N_{b,Rd}} + \frac{0.4M_{T,Ed} + M_{add,Ed}}{M_{T,Rd}} \leq 1.0$$

where

$$M_{T,Ed} = \frac{V_{Ed} a_{eff}}{4} + N_{T,Ed} w_{vier,add}$$

where

$N_{T,Ed}$ is the compression force in the top Tee resulting from global bending

$N_{b,Rd}$ is the buckling resistance of the top Tee

$M_{T,Ed}$ is the moment in the Tees due to Vierendeel bending combined with an eccentricity due to the relative deflection across the opening

$M_{T,Rd}$ is the bending resistance of the Tee

$M_{add,Ed}$ is the moment due to the loading applied over the opening

$w_{vier,add}$ is the relative deflection across the opening in Vierendeel bending, which is calculated at serviceability. In the limit, $w_{vier,add} \leq a_o/200$.

Note: It is assumed that under factored loads, the relative deflection across the opening is $2w_{vier,add}$ and so the additional eccentric moment acting on each Tee due to the relative deflection across the opening is, $N_{T,Ed}\, 2w_{vier,add} / 2 = N_{T,Ed} w_{vier,add}$.

Example for a Slender Tee

As an example of the use of this check for combined actions on the compressed Tee, consider a large rectangular opening in a 13m long beam at x = 5m from one support for the following data:

a_o = 1000mm ($a_o/h_o = 2.22 < 2.5$)

h_o = 450mm and h = 650mm ($h_o/h = 0.69 < 0.75$)

A_f = 220mm × 20mm and t_w =10mm

Q_{Ed} = 30 kN/m; M_{Ed} = 619 kNm and V_{Ed} =45 kN and at x = 5m

Cross-sectional area of Tee, A_T= 220 × 20 + 80 × 10 = 5200mm²

Depth of elastic neutral axis from top of section, z_e = 18mm

Axial resistance of the Tee (for f_y=345 N/mm²) = 5200 × 345 × 10^{-6} = 1794 kN

Bending resistance at the opening, $M_{o,Rd}$ = 1794 × (650 – 2 × 18) × 10^{-3} = 1102 kNm > 619 kNm

Compression force in top Tee, $M_{T,Ed} = \dfrac{619 \times 10^3}{650 - 2 \times 18} = 1008$ kN

Inertia of Tee in vertical direction, I_T = 2265 × 10^3mm⁴

Radius of gyration of Tee, $i_{zz} = \left(\dfrac{2265 \times 10^3}{5200}\right)^{0.5} = 20.9$mm

Slenderness of Tee, $\lambda_T = \dfrac{0.5 \times 1000}{20.9} = 24$

Non-dimensional slenderness, $\bar{\lambda}_t$ = 24/77 = 0.31

For buckling curve (c) considering the Tee as a strut, its buckling resistance is obtained as χ_T= 0.93.

Buckling resistance of Tee, $N_{b,Rd}$ = 0.93 × 1794 × 10^{-3} = 1668 kN > 1008 kN

Vierendeel bending moment acting on a Tee, $M_{T,Ed}$ = 45 x 1.0/4 = 11.3 kNm

Plastic bending resistance of Tee, $M_{T,Rd}$= 21.1 kNm

Additional end moment due to local load on Tee, $M_{add,Ed}$ = 30 × 1.0²/12 = 2.5 kNm

Eccentricity of the axial force due to the deflection across the opening for V_{ser} = 31.6 kN:

$$w_{vier,add} = \frac{31.6 \times 1.0^3 \times 10^9}{24 \times 210 \times 2265 \times 10^3} = 2.8\text{mm } (=a_0 / 355)$$

This satisfies the deflection limit of a_o/200 across the opening at serviceability.

The additional eccentric moment due to the relative deflection across the opening is,

$N_{T,Ed}\, w_{Vier,add}$ = 1008 × 2.8 × 10^{-3} = 2.8 kNm

Verification of the combined buckling and bending resistance of the top Tee:

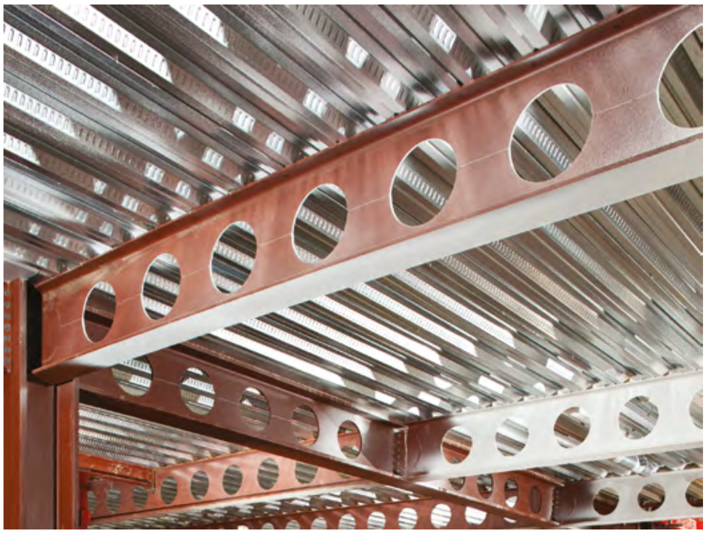

Figure 2 - Typical slender bean with infills (courtesy of Kloeckner UK Metals Westok)

$$\frac{1008}{1668} + \frac{0.4 \times (11.3 + 2.8) + 2.5}{21.1} = 0.60 + 0.39 = 0.99 < 1.0 \text{ just OK}$$

This shows that the 100mm deep top Tee is stable under combined loads for a 1m long opening.

Checks on End-Posts

The design of end -posts next to connections is an aspect not properly covered by SCI P355 and is now addressed in BS EN 1993-1-13. This will be covered in a subsequent article in *New Steel Construction*, based on tests on cellular beams at City University of London. The minimum width of an end-post in a cellular beam with circular openings is given as 0.25 h_o, and for rectangular openings, the minimum width increases to 0.5 a_o. ■