Design of End-Posts to BS EN 1993-1-13: Beams with Large Web Openings

In a first article last month, Mark Lawson of the Steel Construction Institute presented an outline of the new BS EN 1993-1-13. This second article presents results of tests on end-posts in cellular beams at City, University of London.

In the recently published BS EN 1993-1-13 Beams with large web openings, a new method is given for the design of end-posts, which is the part of the web next to an end connection. This was missing in previous guidance to SCI P355. Often, it is necessary to introduce a half or full infill plate next to the connection to satisfy the dimensional limits and to achieve the required design shear resistance.

Two generic connection types may be considered:

- Bolted shear connections to the beam web either by fin plates or angles.
- Welded end-plate connections in which the end-plate is either connected only to the beam web (partial depth end-plate) or also to the flanges (full depth end-plate)

For end-plate connections, the end-plate strengthens the end-post in horizontal shear and bending, and also partly stabilises the end-post against buckling. Conversely, bolted fin-plate or angle connections lead to a reduction in the shear and bending resistance at the line of the bolt holes and may provide less restraint to end-post buckling.

The design method for end-post buckling given in BS EN 1993-1-13 was compared to the results of tests on cellular beams at City, University of London reported by Tsavdaridis et al. (2024). The tests were on symmetric cellular beam sections with various end-post details and the two connection types noted above.

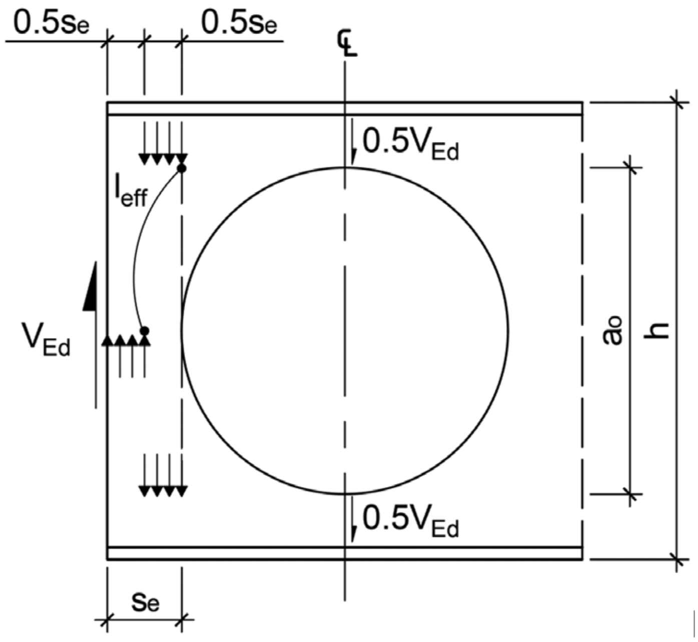

Figure 1 – Illustration of strut buckling model for an end-post in EN 1993-1-13

Buckling of the end-post to BS EN1993-1-13

The design method for buckling of end-posts in EN1993-1-13 is based on an adaptation of the web-post buckling model. This strut action in the end-post is shown in Figure 1. The compression force, $N_{ep,Ed}$, acting on the strut is taken as equal to the shear force in the top Tee, which is $N_{ep,Ed} = 0.5V_{Ed}$ for a symmetric section, and the effective width of the equivalent strut is taken as $b_{eff} = 0.5s_e$, where s_e is the end-post width.

The minimum width of the end-post is given as $s_e \leq 0.25a_o$ in the case of an adjacent circular opening of diameter, a_o , and $s_e \leq 0.5a_o$ for an adjacent rectangular opening of length, a_o.

For an end-post next to a circular opening, the effective length of the equivalent strut is taken as the diagonal distance over half of the end-post width and half of the opening depth. The end-post relative slenderness is:

$$\bar{\lambda}_{ep} = 1.75\frac{(s_e^2 + a_o^2)^{0.5}}{t_w\lambda_1} \leq \frac{2.45a_o}{t_w\lambda_1}$$

where $\lambda_1 = 3.14\ (E/f_y)^{0.5}$

The buckling resistance of the end-post is obtained from buckling curve 'a' to EN1993-1-1.

Modifications to this equation are given an end-post partly stabilised by a full depth end-plate connection, and for an end-post with notches. No guidance is given in EN 1993-1-13 for the use of half or full infill plates to form part of the end-post, although in principle the same theory may be used by replacing t_w by t_i where t_i is the thickness of the infill plate if this is thinner.

The buckling resistance of the end-post should exceed the compression force transferred from shear in the top Tee, which for a symmetric section is given by:

$$N_{ep,b,Rd} = \chi_{ep}0.5s_et_wf_y \geq 0.5\ V_{Ed}$$

Where χ_{ep} is the reduction factor due to buckling of the end-post using the relative slenderness in the above equation.

Example for a partial depth fin plate connection with s_e = 100mm and a_o = 400mm; t_w = 9.0mm; f_y = 355 N/mm²:

$\ell_{eff} = 0.5 \times (100^2+400^2)^{0.5} = 206$ mm

$\lambda_{ep} = 3.46 \times 206/ 9.0 = 79$

$\lambda_1 = 3.14 \times (210 \times 10^3/355)^{0.5} = 76$

$\lambda_{ep} = 79/76 = 1.04$

$\phi = 0.5 \times (1 + 0.21 \times (1.04 - 0.2) + 1.04^2) = 1.13$

$\chi_{ep} = [1.13 + (1.13^2 - 1.04^2)^{0.5}]^{-1} = 0.63$

Buckling resistance, $N_{b,Rd} = 0.63 \times 0.5s_et_wf_y = 0.63 \times 50 \times 9.0 \times 355 \times 10^{-3} =$ 100.6 kN

For a symmetric section, it is required that $0.5V_{Ed} \leq N_{ep,b,Rd}$, and so the maximum end shear force that may act at the connection is $V_{Ed} \leq 201$ kN.

Comparison with tests on end-posts in cellular beams

A series of 3 cellular beams, each with two types of connections, was tested to compare with the design method for end-posts and these tests were reported by Tsavdaridis (2024). The test configuration is shown in Figure 2 (over page) and the details of the tests were:

- Cellular beams of h = 560mm depth using 406 × 178 × 67 kg/m UB sections.
- Opening diameter, a_o = 400mm (a_o = 0.71h).
- Beam span, L = 3.63m with jack loads applied at 0.82m from the supports.
- S355 nominal steel grade (measured as f_y = 393 N/mm²)
- Columns, 203 × 203 × 60 kg/m UC sections (1m high).

The two connection types were:

- End plate connections using a 12mm thick end plate with 2 × 4 no. M20 bolts to the column flange.
- Fin plate connection using a 12mm thick projecting welded plate of 440mm depth with 5 no M20 bolts to the beam web.

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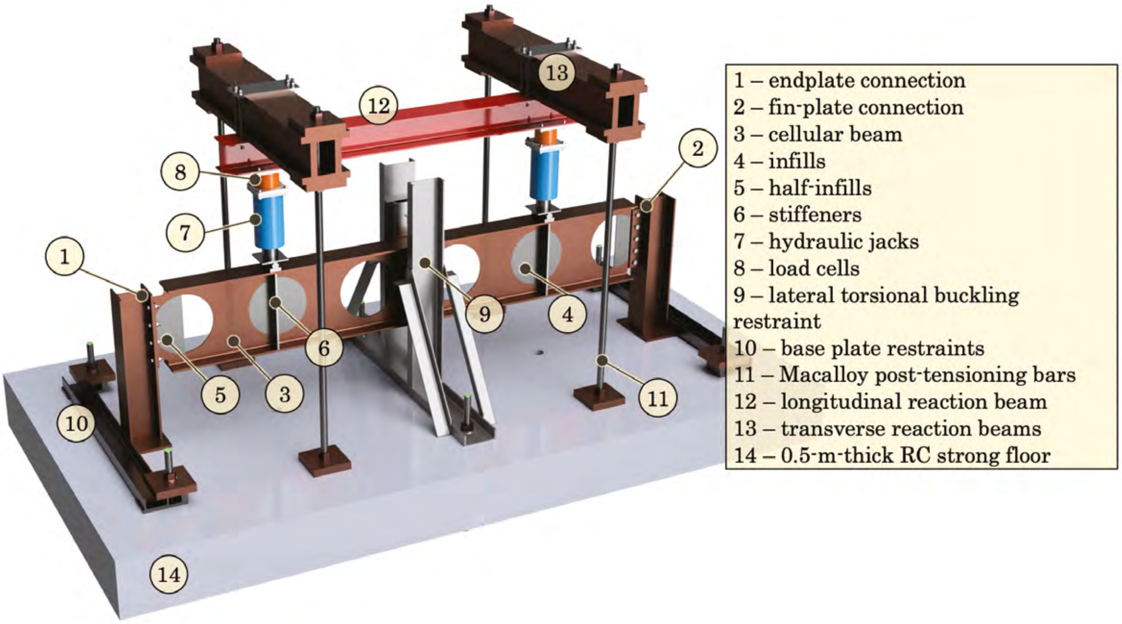

Figure 2 - Graphic of the loading system for the cellular beam tests (Tsavdaridis et al, 2024)

►24 The three forms of end-post combined with the two connection types were:

- Narrow end-post of 90mm width ($s_e = 0.225a_o$).
- Narrow end-post with 90mm wide × 60mm deep notches to both flanges with a 20mm radius corner of the notch.
- End-post formed by 200mm wide half infill of 9mm measured thickness.

Full infills and web stiffeners were used at the loading positions.

The mode of failure of the narrow end-post next to the notched flange at a shear force of 298 kN is shown in Figure 3. The same beam with a half infill plate shown in Figure 4 failed at a shear force of 398 kN, in this case by buckling of the infill plate.

Test details	Connection type	Failure shear in test	End-post buckling to BS EN 1993-1-13	Mode of failure
90mm wide end-post	Fin plate	325 kN	188 kN	End-post bending
	Full depth end-plate	331 kN (+2%)	197 kN	Vierendeel bending at opening
90mm wide end-post with 90x60mm notches	Fin plate	279 kN	178 kN	Buckling at notch
	Partial depth end-plate	298 kN (+7%)	193 kN	Lateral movement of flange at notch
Half infill plate (200mm wide) with 90x60mm notches	Fin plate	398 kN	263 kN	Buckling of half infill plate
	Partial depth end-plate	417 kN (+5%)	279 kN	

Table 1 - Test shear failure loads of end-posts and comparison with the design predictions using the measured steel strength

Figure 3 - Buckling at narrow end post for the notched cellular beam

Figure 4 - Buckling of the half infill plate due to the transfer of shear from the top Tee

The test shear failure loads are presented in Table 1 in comparison to the prediction of the design to BS EN 1993-1-13 using measured material strengths. The ratio of the test failure shear to the design prediction was in the range of 1.54 to 1.73 for the four tests with narrow end posts. This shows that the proposed method is conservative, probably because of redistribution of shear forces from the compressed top Tee to the bottom Tee in tension after buckling at the notch had occurred.

For the test with half infill plates, the ratio of the failure load to the design prediction was 1.49 and 1.51 and shows that the model for buckling of the infill plate is reasonably accurate.

It is concluded that the design method for end -posts to BS EN 1993-1-13 is relatively conservative when applied to symmetric cellular beams and some improvements could be made based on a parametric study of various end-plate geometries. Based on the test results, the minimum width of an end-post in cellular beams may be potentially reduced to $0.2a_o$ as a Nationally Determined Parameter. ■

Acknowledgements

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References

Tsavdaridis, K.D., McKinley, B., Corfar, D-A, Lawson, R.M. (2024) *Cellular Beam End-posts with Two Connection Types, End Notches and Infill Plates. Journal of Constructional Steel Research*, 215, article number 108547.