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Design of Asymmetric Cellular Beams:
Application limits of SCI Publication P-100

Introduction

Cellular beams have become the vogue for many long span applications both in the UK, and increasingly in France. Often cellular beams are designed in buildings with strict height limitations such as in renovation applications, or in the French experience, to compete directly with concrete flat slab construction. To satisfy both serviceability requirements and the need to install reasonably large service ducts, cellular beams are increasingly designed with highly asymmetric sections and large openings off-centre with respect of the beam depth. In addition, the size of the bottom Tee, cut from a rolled steel section, can be increased disproportionately to the top Tee to achieve the required natural frequency limit. In such cases, there is a considerable reserve in bending and shear resistance for these long span beams.

From the structural design point of view, these new designs of cellular beams have moved considerably from those envisaged in the SCI publication P-100. SCI is working with European partners in an ECSC project to prepare application rules for composite beams with rectangular and circular openings consistent with Eurocode 4. SCI publication P-100 is used as the basis of design, but it is also necessary to extend the application to cover a wider range of design cases, one of which is the use of highly asymmetric composite cellular beams. Furthermore, both Eurocode 3 and BS 5950 Part 1: 2000 now increase the design shear resistance that can be developed in the Tees by at least 10% (due to the increase of the 0.9 factor on shear area to 1.0), and so it is necessary to have more accurate methods of analysis consistent with the higher stresses permitted by these new Codes.

Design Model

Asymmetry in the cross-section of cellular beams can arise from both the relative area of the Tees and from the position of the openings in the beam depth. Internal forces in the web post depend on the rate of increase of axial forces in the Tees and on the differential shear forces resisted by the Tees. The equilibrium of the top and bottom Tees in composite beams is illustrated in Figure 1. Ideally, the shear forces resisted by the Tees (including the concrete slab) should be similar. For severely asymmetric sections, redistribution of shear forces between the Tees causes an in-plane moment in the web post, and the ability to resist this moment depends on the width of the web post.

Equilibrium is established in the Tees when the in-plane moment M_h, acting on the web post, is determined according to the following equation:

$$M_h = (V_b - V_t - V_c)\, s_o/2 - V_h\, e + \Delta C\,(D_{s,eff} + x_t)/2$$

where
- V_b is the shear force in the bottom Tee
- V_t is the shear force in the top Tee
- V_c is the shear force in the concrete
- V_h is the horizontal shear force in the web post ($=\Delta T$)
- s_o is the centre to centre spacing of the openings
- e is the eccentricity of the centre-line of the opening above the mid-height of the beam
- x_t is the distance of the centroid of the top Tee from the top of the beam
- $D_{s,eff}$ is the depth of the slab to centre of compression
- ΔC is the increase in compression force in the slab due to the shear connectors in length, s_o.
- ΔT is the increase in tensile force in the bottom Tee in length, s_o.

As all parameters, except V_t and V_b are known, the relative magnitude of the shear forces in the Tees can be selected to minimise M_h. If there is a reserve in shear resistance, M_h can be set to zero. If not, this moment can be resisted by the web-post based on its elastic bending resistance at its narrowest section. The effect of horizontal shear may be taken into account by retaining a factor of 0.9 on the shear area of the web, as in BS 5950 Part 1: 1990 (BS 5950 Part 1: 2000 increased this factor from 0.9 to 1.0 for plates).

For web-post buckling, the effect of in-plane moment moves the point of zero bending towards the weaker Tee. The moment acting on a critical plane of 0.45 d_o above the centre-line of the openings is determined according to:

$M_{wb} = 0.45\, d_o V_h - M_h$ for the top Tee

and $M_{wb} = 0.45\, d_o V_h + M_h$ for the bottom Tee

d_o is the diameter of the opening

Web-post buckling is checked using Mwb as in SCI P 100. Therefore, the effect of M_h is beneficial when the bottom Tee is heavier than the top Tee, which is normally the case.

Simplified Rules

Clearly, it is difficult to make a hand calculation for these effects, and so in design, it is best to minimise M_h. The following general advice is offered for the design of highly asymmetric sections:

- design for a Utilisation Factor in vertical shear of less than 0.7, which allows the weaker Tee to resist half of the applied shear force
- keep within a reasonable degree of asymmetry of the Tees, typically less than 2:1 in terms of web area of the Tees
- choose the width of the web post to be not less than half of the opening diameter so that the web post can resist the moment M_h easily

The following table has been determined to assist the designer in choosing the maximum degree of asymmetry in web area for scheme design, based on a cell spacing to diameter ratio of not less than 1.5. In all cases, the minimum depth of Tee is 0.1 × beam depth.

Utilisation Factor for Vertical Shear	1.0	0.9	0.8	0.7	≤ 0.6
Maximum Ratio of Web Areas of Tees	1.2	1.5	2.0	2.5	3.0

Table 1. Maximum asymmetry of Tees in terms of web area.

Design outside these limits should account for asymmetry of the Tees in terms of web area, as presented above.

Future Testing and Development

The SCI is working closely with RWTH Aachen (Germany), Arbed Recherches (Luxembourg), CTICM (France), and the University of Lulea (Sweden) to devise a range of full-scale structural tests on composite beams with web openings of various types to provide performance data for:

- highly asymmetric beams
- slender (Class 4 webs)
- elongated openings
- practical stiffening arrangements
- fire engineering

This work is needed in order to develop application rules in the wider European context, where experience is less than in the UK.

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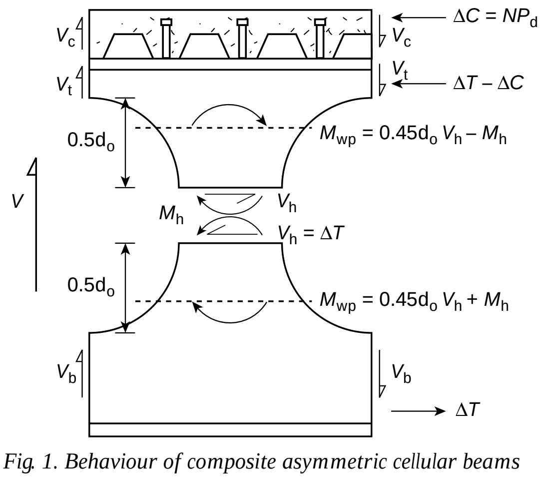

Fig. 1. Behaviour of composite asymmetric cellular beams