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Analysis and Design of Cellular Beam and its Verification

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Abstract

The behavior of cellular beam is described using design methods according to BS: 5950, considering particularly the strength of tee sections and web post element. Such behavior is derived from parametric study involving finite element analysis using software ANSYS. The design method is based on plastic analysis of beam section at ultimate loads and elastic analysis at serviceability loads. The procedure of design of cellular beam is illustrated and an example based on design method is worked out and its verification is done for checking the suitability.

Key words: Cellular beam; vierendeel bending; web post flexural and buckling strength.

1. Introduction

I- shaped steel sections are widely used as main structural element as beam and column in various building structures. It is advantageous to have web perforations, especially in beam elements, to allow for the passage and installation of piping, duct works and electrical conduits without increasing the floor to floor height, resulting in saving in amount of steel used. Such perforations of circular shape are widely used called cellular beam. The presence of web opening requires checking structural adequacy and characteristics. The performance of such beam such as load carrying capacity and failure modes are investigated through design methods and finite element analysis. Such design methods are described in BS: 5950 part 1, part 3.1and SCI publication 100.

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1.1 Guidelines for web perforations

The limits of applicability are:

a) $1.08 < S/D_0 < 1.5$ b) $1.25 < D/D_0 < 1.75$

Where S= centre /centre spacing, Do= Diameter of opening, D= Total depth of beam

1.2 Ultimate limit state

To check the beam for the ultimate limit state condition, it is necessary to check the overall strength of the beam the strength of its elements. The following checks should be carried out:

- Overall beam flexural capacity.
- Beam shear capacity (based on the reduced section)
- Overall beam bucking strength.
- Web post flexure and bucking.
- Vierendeel bending of upper and lower tees.

1.2.1 Overall beam flexural capacity:

The maximum moment under factored dead and imposed loading, M_u should not exceed M_p, where M_p is calculated as follows:

$M_u \leq M_p = A_{Tee} P_y h$

Where A_{Tee} =area of lower Tee, P_y =yield stress of steel (Grade 50),

h = distance between centroids of upper and lower tee.

1.2.2 Beam shear capacity

Two modes of shear failure should be checked. The vertical shear capacity of the beam is the sum of the shear capacities of the upper and lower tees. The factored shear force in the beam should not exceed P_{vy} where:

$P_{vy} = 0.6 \times P_y$ (0.9 ∑ area of webs of upper and lower tees)

In addition, the horizontal shear in the web post should not exceed P_{vh} where:

$P_{vh} = 0.6 \times P_y$ (0.9 x minimum area of web post)

Horizontal shear is developed in the web post due to the change in axial forces in the tee.

1.2.3 Interaction of axial and high shear forces

In BS 5950 part 1 clause 4.2.6, the interaction between axial forces (or bending moment) and shear in the web of beam is based on a linear reduction of axial or bending capacity for forces exceeding 0.6 Pv. It follows that as the shear force given above approaches Pv, the axial or bending capacity of the web portion of the web tee reduces to zero.. This interaction may be taken into account by modifying the web thickness depending on the shear force resisted by the web.

1.2.4 Overall beam buckling strength

To assess the overall buckling strength of a cellular beam, it is recommended that beam properties are determined at the centre line of the opening and that lateral torsional buckling strength is then determined in accordance with BS 5950: part 1, section 4. If the compression Flange is restrained sufficiently, this check may not be necessary.

1.2.5 Web post flexural and buckling strength

The web post flexural and buckling capacity should be checked using the equation:

$$\frac{Mmax}{Me} = [C_1 (\frac{S}{D0}) - C_2 (\frac{S}{D0})^2 - C_3]$$

Where M_{max} = maximum allowable web post moment.

Me = web post capacity at post section = elastic section modulus x Py

And $C_1\ C_2\ C_3$ = are constants evaluated as follows:

$C_1 = 5.097 + 0.1464\ (\frac{D0}{t}) - 0.00174\ (\frac{D0}{t})^2$,

$C_2 = 1.441 + 0.0625\ (\frac{D0}{t}) - 0.000683\ (\frac{D0}{t})^2$,

$C_3 = 3.645 + 0.0853\ (\frac{D0}{t}) - 0.00108\ (\frac{D0}{t})^2$

1.2.6 Vierendeel bending of upper and lower tees:

The critical section for the tee should be determined by using one the methods as described by Olander's or Sahmel's approach. The combined forces in the tee should be checked as follows:

$$\frac{P0}{Pu} + \frac{M}{Mp} \leq 1.0$$

Where Po and M are forces and moments on the section at an angle Ө from vertical.

P_u = area of critical section x P_y and Mp = plastic modulus of critical section x P_y for plastic sections

Or M_p = elastic section modulus of critical section x P_y for other sections

The value of M_p depends on section classification.

1.3 Serviceability limit state

To ensure an adequate design, the secondary deflections occurring at the opening should be added to the primary deflections due to overall bending of the beam. The total deflection of the beam is found out by summation of deflection due to shear in tee and web post and bending in tee and web post for each opening. The shear force leads to additional deflections. The maximum deflection should not exceed span/200 for all other beams as per BS: 5950 part 1.

2. Example

Design A simply supported cellular beam carrying load of 12.39 kN/m and span of 10m. Grade of steel =50, Design strength = Py = 355 N/mm^2

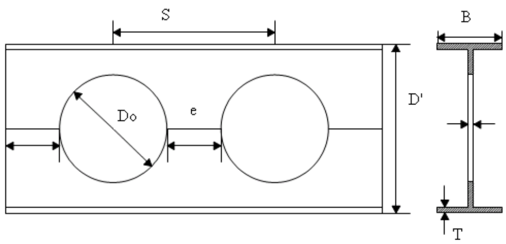

Fig 1 Beam with circular opening

Try UB ((457 x 191 x 67) (Grade 50) – from BS – 5950

UB section properties and dimensions:

Overall depth D' = 453.6 mm, Width of flange B = 189.9 mm,

Thickness of web t = 8.5 mm, Thickness of flange T = 12.7 mm, Area of cross section A = 85.4 mm, Depth of opening D_0 = 400 mm, Spacing S = 600 mm

Cellular beam properties and dimensions:

Depth of cellular beam = D = 626.8 mm and use 16 no. of openings
S/D_0=1.5 and D/D_0 = 1.57 o.k.
Classification of cellular Beam: as plastic.
A = 6534.5 mm^2, I = 5.6357 x 10^8 mm^4, Z_x = 1.798 x 10^6 mm^3 S_x = 1.910 x 10^6 mm^3
M_p = (elastic) = $Z_x P_y$ = 638.3 kN.m, M_p = (plastic) = $S_x P_y$ = 678.1 kN.m
Properties of Tees:
A_{tee} = 3267.7 mm^2, Mp (plastic) = 19.6 kN- m, Pu = A_{tee} Py = 1160 kN.

2.1 ULTIMATE LIMIT STATE Design using construction stage loading:

Total load = 4.13 kN/m^2
Bending Moment = (Maximum moment) = 154.9 kN.m

Table 1: Internal Forces and Moments and its verification using **Finite element analysis software (ANSYS)**

Position	X(m)	V (kN.)	**V(kN) ANSYS**	M(kN.m)	**M(kN-m) ANSYS**	T(kN)	V_h(kN)	**V_h(kN) ANSYS**
0	0	61.95	-	0		0	0	
1	0.2	59.47	**59.43**	12.14	**12.1**	20.77		
2	0.5	55.76	**55.71**	29.43	**29.4**	50.36	53.40	**52.87**
3	1.1	48.32	**48.28**	60.65	**60.6**	103.8	45.8	**45.87**
4	1.7	40.89	**40.85**	87.41	**87.3**	149.6	38.1	**38.21**
5	2.3	33.45	**33.42**	109.7	**110.0**	187.7	30.6	**30.61**
6	2.9	26.02	**26.00**	127.6	**127**	218.3	22.8	**22.97**
7	3.5	18.59	**18.57**	140.9	**141**	241.1	15.4	**15.28**
8	4.1	11.15	**11.14**	149.9	**150**	256.5	7.5	**7.60**
9	4.7	3.72	**3.71**	154.3	**154**	264.0		
10	5.0	0		154.9		265.1		

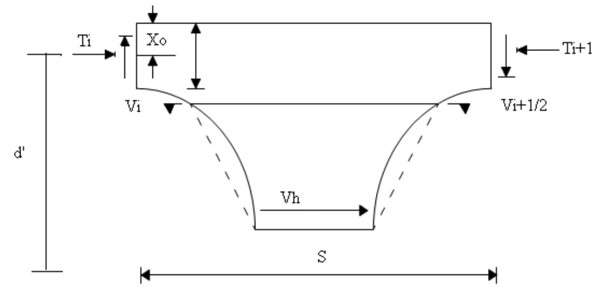

Fig.2 Section of circular beam with forces

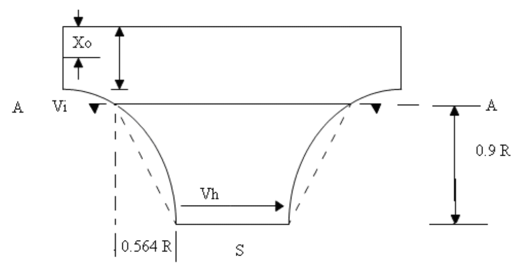

Fig. 3 Section of circular opening

Shear force = V, Bending Moment = M, Axial load = T = M/(2d')

Horizantal shear = $V_h = T_{i+1} - T_i = (M_{i+1} - M_i)/(2d')$, d' = 292.2 mm.

2.1.1 Overall Beam Flexural capacity:
Mu =154.9 kN-m < Mp = 678 kN-m **o.k.**

2.1.2 Beam shear capacity**:**
Shear at support: V_{max} = 61.95 kN and P_v = 1135 kN.
V_{max} = 61.95 kN < Pv = 1135 kN **o.k.**
Shear at opening (tees): V_{max} = 55.76 kN (Maximum) and P_{vg} = 370 kN
V_{max} = 55.76 kN < P_{vg} = 370 kN **o.k.**
Horizontal shear V_h : V_{max} = 53.4 kN (Maximum) and P_{vh} = 326 kN.
V_{max} = 53.4 kN < P_{vh}= 326 kN **o.k.**
2.1.3 Web post strength
$S/D_0 = 1.5$ $D_0/t = 47.06$ $C_1 = 8.1464$, $C_2 = 2.8697$, $C_3 = 5.2674$, $M_{max}/M_e = 0.4954$
at section A-A: from figure 3 ,Z_e = 256608 mm^3, M_{max} = 45.13 kN- M., Maximum V_h = 53.4 kN.
There fore, Maximum moment at A-A = 9.61 kN- m **o.k.**

2.1.4 Vierendeel bending of Tees:
Check should be made at several sections to establish critical section. Check capacity for each opening.
At $\Theta = 0$ of opening with maximum vertical shear.
Vertical shear on tee = V_{max} = 27.88 kN , Shear resistance of tee = P_{vg} = 185 kN.
V_{max} = 27.9 kN < 0.5 P_{vg} = 92.5 kN.
Therefore, No reduction in effective thickness of web i.e. t_e =t; this applies to all openings.
Assume critical section is at $\Theta = 25^o$, Mp (plastic) = 31.7 kN -m
P_v = 237.6 kN , Pu = Ap_y = 1341.9 kN , (shear < 0.5 Pv, therefore, ignore axial-shear interaction)
Force on section at $\Theta = 25^o$, $P_0 = T \cos 25^o - (v/2) \sin 25^o$, $M = 4.72\ T + 134.1\ (v^2/2)$ (kN-mm)

Table 2: Combined moment and axial forces at various positions

Position	T(kN)	v/2 (kN)	P_0 (kN)	M (kN-m)	$P_0/P_u + M/M_p$
2	50.36	27.88	33.86	3.98	0.15
3	103.8	24.16	83.86	3.73	0.18
4	149.6	20.45	126.9	3.45	0.20
5	187.7	16.73	163.0	3.13	0.22
6	218.3	13.01	192.3	2.78	0.23
7	241.1	9.30	214.6	2.39	0.24

Therefore, $\Theta = 25^o$, $P_0/P_u + M/M_p < 1$ **o.k.**

2.1.5 Simplified deflection calculation:
Assume I = I of beam with openings = 5.6357 x 10^8 mm^4 and increase deflection by say 25% to allow for shear deformation:
Deflection = $((5 \times 2.38 \times 3 \times 10 \times (10 \times 10^3)^3) / (384 \times 2.1 \times 10^2 \times 5.6357 \times 10^8)) \times 1.25$ = 9.82mm. **o.k.**

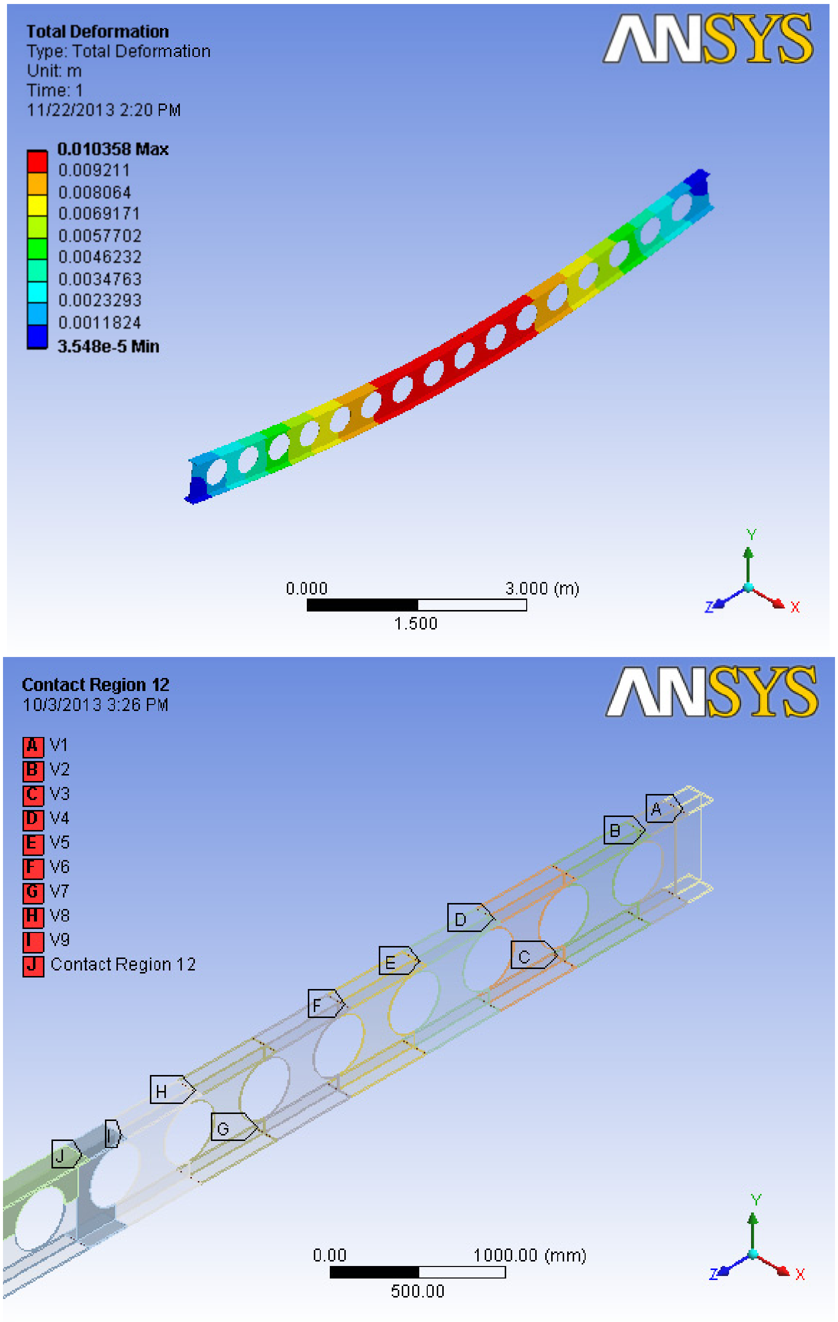

Fig 4: Deflection of 10.358mm and locations for forces and moment

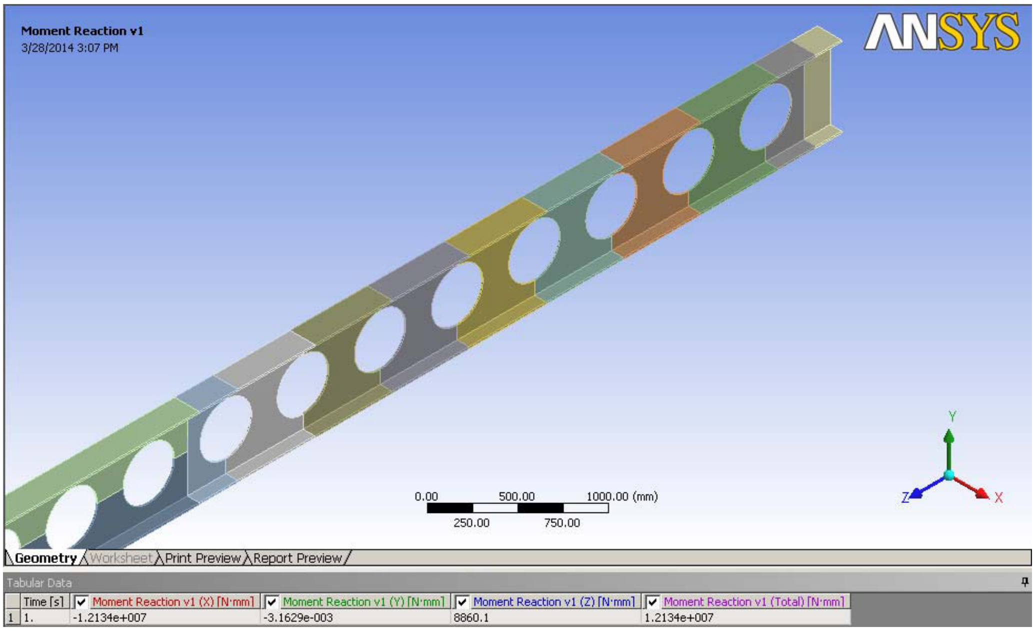

Fig 5: Moment at section 1

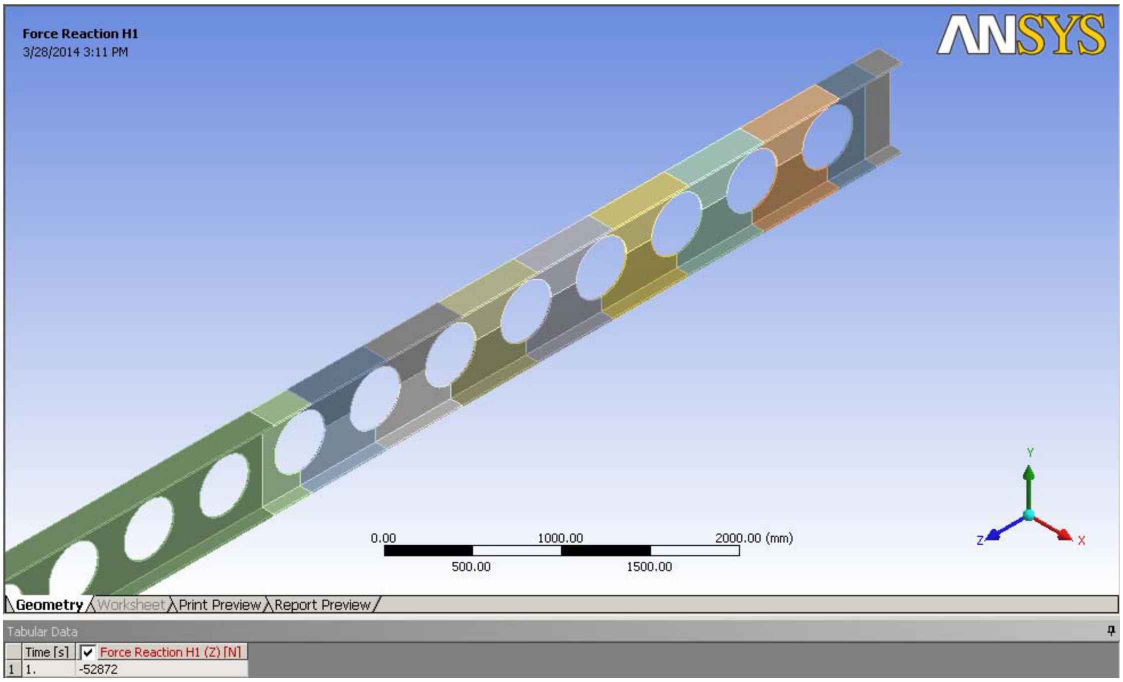

Fig 6: Horizontal force at section 1

3. Conclusion

A cellular beam is designed in accordance with BS: 5950. The same beam is analysed using finite element analysis software (ANSYS) and all results are verified. The geometry of cellular beam is modelled and loaded accordingly. The deflection, bending moment, shear force and horizontal force at various sections of beam is calculated theoretically and the observed results from finite element analysis software are presented in tabular form. The variation in results for theoretical and using software ANSYS is less than 5%, this is due to dimensional linearity, material properties and localized effect of three dimensional modelling in ANSYS. Hence the applicability of such code of practice can be observed. Such design method can be applied to various beam sections with different opening ratios and spacing. Web stiffeners can be applied under point loads, near the support for strengthening of beams.

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