Buckling Analysis of Cellular Beams

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***Abstract* - Castellated beams are those beams which has openings in its web portion. Use of castellated beams has become very popular now a days due to its advantageous structural applications. This is due to increased depth of section without any additional weight, high strength to weight ratio, their lower maintenance and painting cost. The openings made in the webs are of generally hexagonal, circular, diamond or square in shape. Therefore, considering structural performance of the beam, the size and shape of openings provided in the web are always an important issue of concern. In this paper a steel section is selected,different castellated beams are fabricated with different web openings. The finite element analysis (FEA) of the beams using Ansys 14.5 software was done. Buckling analysis of the web post as a failure mode of castellated beam has been studied and concluded that cellular beam is best for structural applications. In this paper, parametric study of cellular beams has been carried out to optimize its size by considering the ratio of spacing of opening to the depth of opening (S/Do) and various buckling loads were calculated. Analytical study is also done by varying different parameters in cellular beam such as cell diameter , cell spacing , cell shape. It was observed that the cellular beams failed mainly due to Vierendeel mechanism. An optimum design for cellular beams were also studied based on Eurocode 3.**

***IndexTerms* - Buckling, castellated beam, cellular beam, finite element analysis, optimization of web openings, strut analogy, vierendeel mechanism, web openings, web post.**

I. INTRODUCTION

Structural engineers have always tried to find new ways to improve the practices in the design and construction of steel and composite buildings so that the overall cost can be decreased. Beams with web openings and open web- expanded steel beams are some of these ways. Web openings with different geometrical properties have been used for many years to pass duct work or utilities through the web holes in order to decrease floor height and constructional cost of large scale buildings. This is because; decrease in story height reduces interior volume and exterior surface of building and these results in cost saving. Furthermore, in comparison with solid web beams, web-expanded beams can easily increase the shear capacities, vertical bending stiffness and capacities of structure.Steel I-beam sections can be modified to intensify their strength by creating an open-web expanded section from an original solid beam. This is achieved by cutting the web of a solid beam in a certain pattern and then re-welding the two parts to each other. As a result of these cutting and re-welding processes, the overall beam depth increases which in return causes increase in the capacity of the original section. There are two common types of open web expanded beams: with hexagonal openings, also called castellated beams and beams with circular openings referred to as cellular beams. Castellated and cellular beams have been used in various types of constructions for many years. The most common structure types built using these beams are office buildings, car parks, shopping centers and any structure with a suspended floor. Web-expanded beams provide a very economical solution for producing tapered members, which have been used extensively in big sports stadiums [1].

II. FAILURE MODES OF WEB-EXPANDED BEAMS

There are mainly six different failure modes of these beams according to experimental tests carried out by Kerdal and Nethercot on web-expanded beams. These failure modes are caused by beam geometry, web slenderness, type of loading, and provision of lateral supports. Under applied load conditions, failure is likely to occur due to one the following modes [1]:

- Formation of a Vierendeel mechanism
- Lateral torsional buckling of the entire span
- Lateral torsional buckling of the web post
- Rupture of the welded joint
- Web post buckling
- Formation of a flexure mechanism

III. STRUT ANALOGY

Compressive and tensile forces act across the web-post on opposite diagonals, as illustrated in **Figure 1**. Failure occur when a local web buckle form adjacent to the web opening as shown by the shaded areas in Figure. The compressive stress acting on the strut is calculated using the force in the upper tee-section or half the applied vertical shear force for a symmetrically placed opening.The effective width of the web-post resisting compression is taken as the half the total width of the web-post.

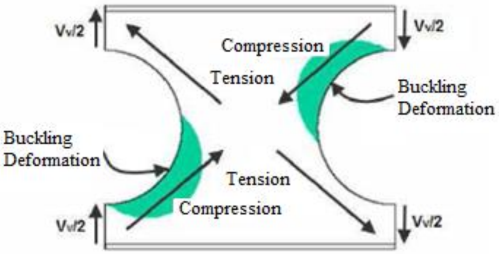

Fig. 1 Typical web-post behavior

IV. FINITE ELEMENT MODELLING

The finite element analysis (FEA) of the beam was done using Ansys 14.5 software. A standard rolled steel I beam is chosen from steel tables which is ISMB 600 and solid186 is been used for modelling. Both the ends of the beam were taken as fixed.The openings made in the webs are of generally hexagonal, circular, diamond or square in shape. Therefore, considering structural performance of the beam, the size and shape of openings provided in the web are always an important issue of concern. Buckling analysis of the web post as a failure mode of castellated beam with different cutouts in beam has been studied and concluded that cellular beam is best for structural applications " [4], [5] ".

V. ANALYSIS OF SOLID BEAM WITH ELLIPTICAL PERFORATIONS

Buckling analysis of castellated beam with elliptical cutouts in different orientations in a solid beam was studied.

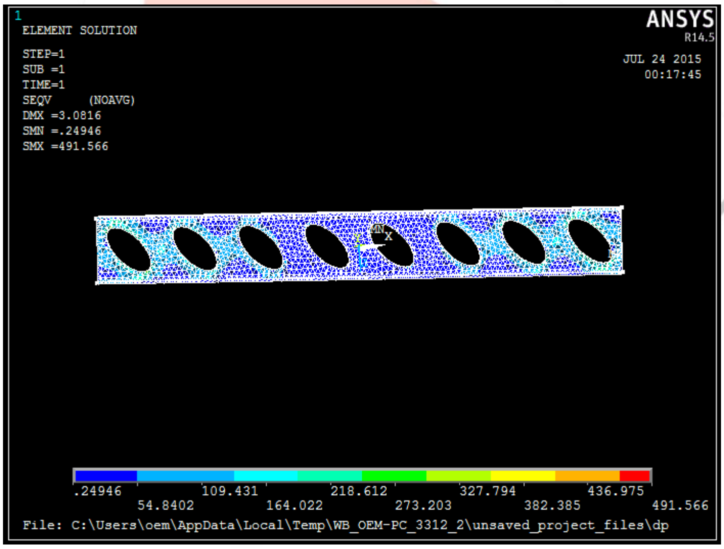

Fig. 2 Vonmises Stresses of the beam

Table 1 : Finite-Element (FE) Analysis Results

Sl no.	Beams	Max. Vonmises Stress (MPa)	Max. Buckling (mm)
1.	Cellular beam	339.02	0.9998
2.	Beams with elliptical cutout at 90°	638.04	1.0004

3.	Beams with elliptical cutout at 180°	451.436	1.000009
4.	Beams with elliptical cutout at 45°	491.566	0.9999

It is clear from above table that beams with elliptical cutouts at 45^0 behaves same as cellular beams which shows more Vonmises stresses. Also beams with elliptical cutout at 90^0 shows maximum Vonmises stresses compared to all other cutouts.

VI. PARAMETRIC STUDY

Buckling analysis of beams with different cell diameters were studied inorder to find optimum spacing to diameter ratio.

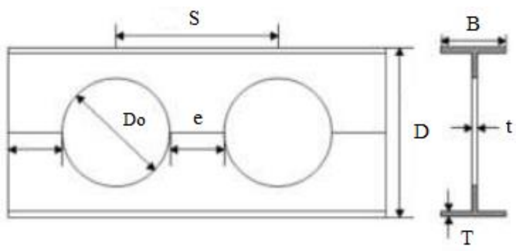

Fig. 3 Geometric parameters of cellular beam

Parameters of cellular beam are
S = centre /centre spacing , Do = Diameter of opening , D = Total depth of beam , B = width of flange of I beam ,
T = thickness of flange of I beam ,t = thickness of web of I beam , e = Clear distance between two opening .

VI.1 Analysis of cellular beam with different S/Do ratio

Buckling analysis of beams with S/Do ratio 1.05,1.08,1.2,1.4,1.5,1.6 where studied.

Due to opening effect, various failure modes are expected to happen. Vierendeel mechanism is the most common failure for perforated steel beams. Vierendeel mechanism is caused the failure due to the formation of four plastic hinges in the top and bottom tees as shown in **Figure 4**. The shear force, which transfers across the opening, causes some secondary moments (Vierendeel bending) in the top and bottom tee sections. Interaction of the secondary moments with the global bending moments and their corresponding local axial force dominates the formation of plastic hinges in the tees “ [3], [4] ”.

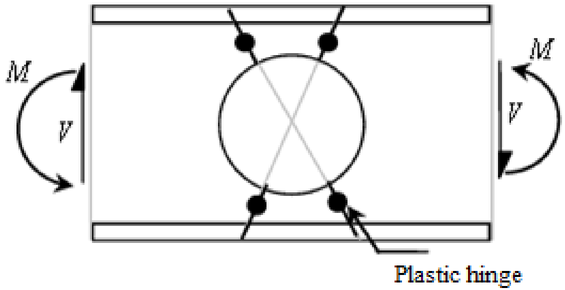

Fig. 4 Vierendeel failure

Table 2 : Buckling Load For Different S/ Do Ratio

Sl no.	S/ Do Ratio	Buckling Load (N)	Buckling (mm)
1	1.05	105.33	1
2	1.08	112.9	0.925
3	1.2	180.86	0.899
4	1.4	213.112	0.801

5	1.5	225.63	0.707
6	1.6	251.8	0.604

It is clear from **Table 2** that buckling load increases whereas buckling decreases with S/Do ratio.

VII. DESIGN OF CASTELLATED BEAM AS PER EUROCODE 3

Guidelines For Perforations In Web

The perforations made in the web greatly affect the structural performance of the beam. Therefore, it is essential to make some logical and practical considerations while providing perforations in the beam. Following are the general guidelines which are given by Eurocode and some of them are based on the field or practical considerations. These standards in web perforations can be changed or modified without affecting the structural performance of the beam.
These guidelines are as follows:
A) Design criteria:

1) Guidelines for web perforations
The limits of applicability are:
a) $1.08 < S/Do < 1.5$
Where S = centre /centre spacing, Do = Diameter of opening, D = Total depth of beam

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:
a) Overall beam flexural capacity.
b) Beam shear capacity (based on the reduced section)
c) Overall beam bucking strength.
d) Web post flexure and bucking.
e) Vierendeel bending of upper and lower tees.

3) Overall beam flexural capacity:
The maximum moment under factored dead and imposed loading, Mu should not exceed Mp, where Mp is calculated as follows:
$Mu \leq Mp = A_{Tee}\ Py\ h$
$$Mp = A_{Tee}\ Py\ h \qquad (1)$$
Where A_{Tee} =area of lower Tee, Py =yield stress of steel, h = distance between centroids of upper and lower tee.

4) 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:
$P_{vy} = 0.6 \times Py\ (0.9 \sum$ area of webs of upper and lower tees)
In addition, the horizontal shear in the web post should not exceed P_{vh} where:
$P_{vh} = 0.6 \times Py$ (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.

5) 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.

6) 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.

7) Web post flexural and buckling strength:
The web post flexural and buckling capacity should be checked using the equation.
$$\frac{Mmax}{Me} < \left[C1 \left(\frac{S}{D0}\right) - C2 \left(\frac{S}{D0}\right)^2 - C3 \right] \qquad (2)$$
$$\text{Where } C1 = 5.097 + 0.1464 \left(\frac{D0}{t}\right) - 0.00174 \left(\frac{D0}{t}\right)^2$$

$$C2 = 1.441 + 0.0625\left(\frac{D0}{t}\right) - 0.000683\left(\frac{D0}{t}\right)^2$$

$$C3 = 3.645 + 0.0853\left(\frac{D0}{t}\right) - 0.00108\left(\frac{D0}{t}\right)^2$$

8) 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:

$$Po/Pu + M/Mp \leq 1 \qquad (3)$$

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

Pu = area of critical section x Py and Mp = plastic modulus of critical section x Py for plastic sections Or Mp = elastic section modulus of critical section x Py for other sections The value of Mp depends on section classification.

9) 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 " [7],[8] ".

B) Fabrication:

Fabrication of Cellular beams is a comparatively simple series of operations when adequate handling and controlling equipment is used. Structural Steel by burning two or more at a time, depending upon their depth. Splitting is performed by using a component of the oxy-acetylene gas cutter equipment. This is an electrically propelled buggy which runs on a fixed track. The buggy has building burning patterns that can be adjusted to any one of live standard longitudinal "module" dimensions and to any hall-opening height.

VIII. CONCLUSION

The Buckling analysis of beam with different perforations has done and results obtained are:

- If the section of beam increases buckling load will also increases and it decreases as the web opening are provided in the section.
- Value of buckling is nearely same for cellular and rectangular web opening of same section of beam whereas vonmises stresses are minimum for cellular beams.Therefore it is concluded that cellular beam is best for structural applications.
- Beams with elliptical cutouts at 45^0 behaves same as cellular beams which shows more vonmises stresses.
- The beam taken for analysis is verified as per Eurocode 3.

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