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Study on Castellated Web Beam with Optimized Web Opening – State of the Art Review

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A B S T R A C T

In this paper, the state of the art of Steel Castellated Beams' manufacturing, applications, and its failure pattern is explained. The current research status of castellated beam activity is not mature and needs a lot to be researched in relation to beams without web openings. The presence of different opening forms such as square, hexagonal, rectan-gular, octagonal and oval etc. in the web beams introduces several additional failure modes, namely; lateral-torsional buckling of web posts, shear force web post buckling, forming of four plastic hinges around the opening corners, rupture of welded joints over traditional steel beams in the castellated beams. To ensure a effective web opening of the castellated beam optimization techniques such as tug of war algorithm, charged system algorithm in MATLAB coding or genetic algorithm are introduced in this paper. Apart from this FEM analysis of experimental and theoretical studies are mentioned considering the impact of different parameters, such as opening forms, opening distance, opening spacing, different number of openings etc.

Keywords:Castellated steel beam, Conventional beam, Lateral-torsional buckling, Vierendeel mechanism, Tug of War Algorithm, MATLAB, Genetic algorithm, FEM analysis

1. Introduction

The structural engineering aspect has been improved by construction technologies in the present era. Today the world is progressing, not only in industrialization, but also in the infrastructure sector, in every market. All metropolitan cities are reaching the sky with high towers, offices, malls, hospitals, construction floor structures, large roof or hall covering structures, so the use of steel as a structural member is becoming increasingly important to meet this need. Due to the versatility and speed of construction, the concept of pre-engineered building (PEB) is most prevalent in steel structures. Such PEBs are long but subject to less loading.

Steel parts are therefore subject to a safe strength standard, but do not meet the serviceability criteria. Therefore to fulfill the need for serviceability, it is essential to use a beam with more width. To overcome this challenge, the best way is to use the open web beam (castellated beam).

A castellated beam is a type of beam in which, by taking advantage of the cutting pattern with a longer web, an I-beam is exposed to a longitudinal cut through its web following a pattern to sever it and reassemble the beam. For castellated beams, using a lighter weight component, the primary application is to span long distances. For spans greater than 30 ft, they are usually feasible and are a very cost-effective alternative for spans greater than 40 ft. Using the long span capabilities of castellated beams, a more open floor plan can be given.

The ability to use castellated beams demands that the longer-spanning, fewer columns and footing components be supported, thereby providing additional column-free space and floor area versatility. It allows fewer members needed, saving for the structure, erection costs, the ability for larger, lighter cycles to be used for a given method. Castellated beams for structures with long open space requirements, beams are suitable, parking garages, industrial parks and factories,Subramanian 2008[1].

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2. Manufacturing

The technique by which castellated and cellular beams are produced is similar, but they are not similar. In addition to a machine-controlled cutting torch, castellated beams are designed with the use of a wide-flange portion of the web to cut a zigzag pattern.

The step-by-step technique of generating a castellated beam is presented in Figure 1-1. The two halves are (b) offset once the segment in the appropriate pattern (a) has been removed. The waste is removed at the ends of the beam (c), and the two sections are welded back together to form the castellated portion (d).

If the web thickness is comparatively thin, without prior beveling of the edges, a complete or partial penetration butt weld is then typically made from one side of the web.Figure 1-2 shows a photograph of the production phase of a castellated beam,AISC 2016 [2].

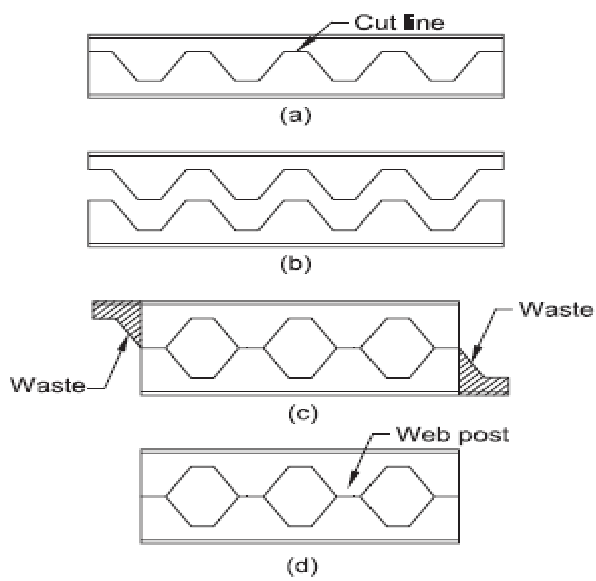

Fig. 2-1. Manufacturing of a castellated beam, Omer,1976[3].

3. Nomenclature

The normal nomenclature for a steel segment indicates the form, approximate width, and weight of the approximate shape per linear foot. It portrays beams with castellated CB beams. The numerical representations are identical to those of standard steel pieces. For example, a castellated beam built from a root beam W8-10 is referred to as a CB12-10 The root beam is about one and a half times that of the root beam and the weight is the same as the root beam. Under such conditions, creating an asymmetric segment is advantageous. In this case, the nomenclature is based on the two separate root beams used to build the castellated beam for these parts.

For instance, if the root beam is a W21-44 for the top tee of the castellated beam and the root beam is a W21-57 for the bottom, then the castellated and call outs will be CB30-44/57 respectively. The first number indicates the estimated width, and the second pair of numbers shows the nominal weight of the root beam used at the top of the section followed by the forward slash, and the nominal weight of the root beam used at the bottom of the section. The sum of the two numbers is the weight per foot of the resulting asymmetrical beam.

4. Applications

This lowers the height of the building when, compared to the traditional approach in which the facilities are positioned below the beams, the clear space between the ceiling and the floor decreases. Savings could amount to up to 0.5 m per storey in such terms.

A more justifiable, compact and cost-effective method of construction is the result of this. A very important consideration is the production method of the above-mentioned perforated beams, as it affects the cost and the structural behavior of the final construction system.

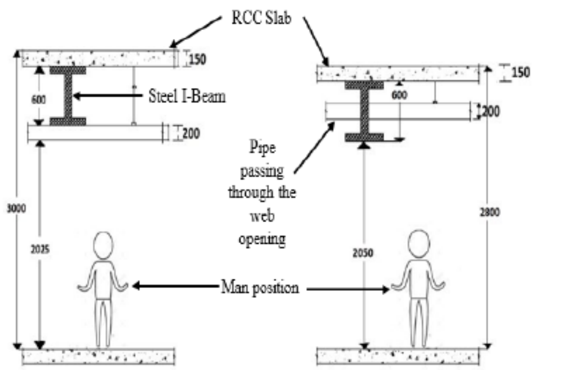

Figure 4-1 - Reduction in height of building storeys, Morkhadeet. al. 2019[4].

5. Types of Castellated Beam

Castellated beams are generally classified on the basis of type or shape of perforations made in the web of beam, Jamadar A and P.D. Kumbhar ,2015[5]. Based on the shape of the opening the various types of castellated beams are shown in figure 5.1,5.2,5.3 and 5.4

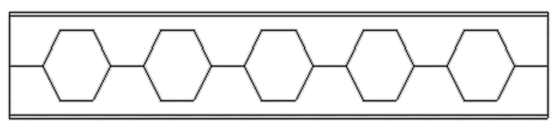

Figure 5-1 Hexongal web Opening

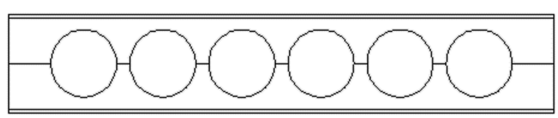

Figure 5-2 Circular web Opening

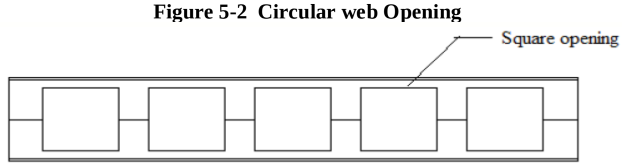

Figure 5-3 Rectangle web Opening

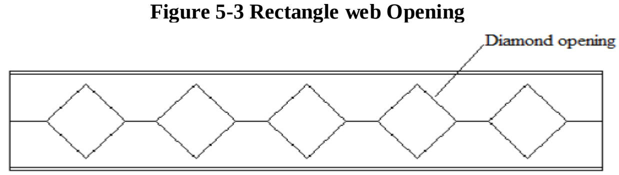

Figure 5-4 Diamond web Opening

6. Terminology of Castellated Steel Beam

Various expressions are used to define the castellated steel beam components as illustrated below:

- Throat Depth: is the web part height between flanges and tee sections.
- Web post: is the solid part cross section of castellated steel beam.
- Throat Width: is a horizontal cutting on parent steel beam.
- Top Tee: Higher part of the beam up of dropping of the throat width.
- Bottom Tee: Down part of the beam under the dropping of the throat width.
- Expansion ratio: Ratio of the increase in depth of the parent beam section to the depth of the castellated section.

All castellated steel beams components are shown in Figure 6.1.,Shakir and et al., 2019[7].

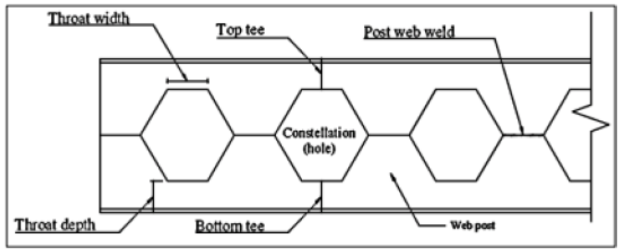

Figure 6-1 - Parts of Castellated beam

7. Various Types of Failure Modes

Following are the modes of the failure of castellated beam.

- Shear mechanism.
- Flexural mechanism.
- Lateral torsional buckling.
- Rupture of welded joints.
- Web post buckling in shear.
- Web post buckling in compression.

Shear mechanism : High shear forces acting on the beam are correlated with this mode of failure. The creation of plastic hinges deforms the tee section above the openings into a parallelogram shape at the reentrant corners of the holes. This mode of failure is prone to beams with relatively short spans with shallow tee sections and longer weld lengths. Higher loads may be borne by shorter lengths, resulting in shear being the governing load. The tee parts above and below the openings must bear the applied shear, as well as the main and secondary moments when a castellated beam is subjected to shear,,Konstantinos Daniel Tsavdaridis& Cedric Mello 2012[8].

Flexural mechanism : The flexural mechanism above and below a castellated beam's openings resembled that of a solid beam with pure bending powers. The distribution of the yield to the central axis was halted due to the presence of holes. This process induces stress and compression in two throat sections before they become completely plastic.,Duggal SK, 2015[9].

Lateral torsional buckling : Lateral The castellated beam's lateral torsional buckling is like the heavy beam. A solid beam is under pressure to bend under applied loads. One of the flange is subject to stress and another to a compression for a purely assisted beam. The parts of the architecture are so proportional in order to reach an economical degree that the moment of inertia on the web's usual concept axis is considerably greater than the moment of inertia on the principal axis parallel to the web, and therefore a component is comparatively poor in the bending resistance of the web normal plane. The low flange, however, appears to stay direct in stress. There are two flanges and a web in the beam reflecting a rigid unit that rotates the entire cross section. This is often followed by bending of the lateral buckling of the compression flange. The beam becomes unstable and can rotate and deflect from side to side, which causes lateral buckling and collapse. If the beam flange compression is constrained laterally enough to overlook this failure mode,,A. J. Mehetre and et al., 2020[10].

Rupture of welded joints : When horizontal shearing stresses surpass the yield strength of the welded joint the mid-depth joint of the web post between two openings will break. The length of the welded seam (e) depends on this mode failure. The horizontal length of the openings corresponds to the length of the weld. And reduced to secondary moments, if horizontal duration is reduced. The webpost's soldered throat is more vulnerable to failure,Ajim S and et al.,2016 [11].

Web post buckling : Web buckling takes place when the strength of vertical compressive stress in close proximity to the center of the section is higher than the critical buckling stress for the web acting as a column. Take a plate girder part in the neutral axis. The complementary shear stress of the same magnitude is produced on the horizontal faces due to horizontal compression above and horizontal tension below the neutral axis. The stresses trigger one diagonal compression and another strain. This compression can cause the web hinge and is called diagonal compression, P.K.Das and S.L. Shrimani, 1984[12].

Web post buckling in compression: The rolling steel parts web is exposed to a significant volume of stress just below the concentrated load, which is above the reactions of the supporting. Thus the web near the concentration of tension begins to fold over the flange. This kind of local humping phenomenon is known as compression web post humping.For over 100 years, the judicious positioning of holes in the network of steel beams has been used to design lighter and stiffer beams. Improved ratio of weight to rigidity, the potential to incorporate construction facilities into the structural depth and the beam's perceived aesthetic appeal,Konstantinos& et al., 2015[6].

8. Research on Castellated Beams - Hexogonal Openings

Wakchaure and Sagade ,2017[13] explained the Bending action of the I-shaped beams castellated with hexagonal openings. The beams were modeled for various web opening depths with varying spacing (S) and opening depth (Do) ratios (i.e.S/De). A two-point load finite-element software program ANSYS14 analyzes of castellated steel beams (I-shaped cross-section) and the support condition is simply supported. It measures the deflection at the center of the beam and analyzes various failure patterns. The beams with increased depths are then comparable with each other and with the parent segment for various criteria and for serviceability purposes. The results show that the castle-lined steel beam performs satisfactorily with regard to serviceability requirements to a maximum web opening depth of 0.6 times the total depth (D). Castellated beams proved effective for moderately loaded distances, where geometries are handled by deflection.

Wakchaure and et al., 2017[14] carried out experiments to research actions by varying hexagonum opening depth (and therefore total depth) in castelated beams under two-point loading (four-point bending). The results show that a beam of 0,6 times the total depth (D) holds the highest load compared to other opening sizes. Researchers have also concluded that fourendeel failure is prevalent with an increase in the opening depth.

The effect of the size and distance of castellated steel beams with hexagonal web openings was studied by Budi et al ., 2016[15]. The comparative analysis was performed using the Finite Element Method (FEM) of cast steel beams. The comparative research will then be carried out by laboratory testing for castellate steel beam specimens of 225 mm height. Six specimens were manufactured from the IWF section at various hole angles from 45, 50, 55, 60, 65 and 70. All models have 150 mm high vertical holes (ho) and range from 0,052ho to 3,15o . Both beams have a clear range of 3000 mm with their simple supports and two concentrated load structures.The results analysis show that the sample volume increases by 1.938 to 2.041, as compared to the initial portion. The best results from the FEM study were a 60o angle specimen and 0.186 to 0.266 hole distance. There is a strong consensus between them between the contrast between FEM and laboratory studies.

Analytical analysis was carried out by Samadhan et al., 2017[16] to compare the loads carrying the power of castellated and solid steel beams. With simple support specifications exposed to a single central load at medium span, ISMB 200 Steel I-Section was adopted. This ratio of castellation is respectively 1.5, 1.6 and 1.8. Finite element analysis was performed with version 12 of ANSYS. The results showed the minimum hole height should not be less than 50% of the section width, the maximum hole width must not be more than 75%, and the best expansion ratio should be 1.5%.

The load carrying capacity of the optimally constructed castellated beam was analysed by Erdal and Saka 2015 [17]by differing numbers of holes and spacing. FEA of the same beams is often done by the implementation of central point load and ANSYS is used to analyse and check failure patterns. Study shows that although the members' lengths are comparatively shorter due to torsional shafts, the beams are tested by lateral supports. The lesson is the beam is broken in fourendeel mode because the load is applied above the openings, while in the web post it does not operate when loads are applied between opening spaces.

9. Research on Castellated Beams : Circular and Diamond Openings

In order to optimize its size, the parametric analysis was conducted of castellated beams with ring beam and diamond-like openings in consideration of the ratio of the overall castellated beam profundity to the given opening depth (D/Do) and the opening spacing ratio with opening depth (S/Do).The P.D.Kumdar and Jamadhar A.M[18] paper explained the analysis of the finite elements (FEA) of the beam using the programmeAbaqus / CAE 6.13 and following the provisions of Eurocode 3 was carried out for various opening sizes. For the evaluation of the beam failure load of misses failure parameters are used and experiments confirm optimized beam results. The results showed that the beam provides better strength results for diamond-shaped openings with an opening size of 0.67 times the total beam depth. Castle beams are also found to collapse in their local modes of failure.

Amol J Mehrtae and et al., 2020[19] paper explains that in the course of testing current literature on the beam power, a rectangular opening and rectangular opening were implemented equal to diagonal and hexagonal opening with different angles 300, 450 and 600 of the opening. The fillet radius is given to the corner of the rectangular opening as a result of 54% improving the carry-force of the rectangular segment compared to the regular rectangular portion.

10. Optimization of Castellated Beams

Kaveh and Shokohi 2014[20] explained the numerical analysis related to cost optimization of the beams and cellular beams has been conducted. For optimisation, the CBO algorithm has been used and beam cost is considered the objective function. The tug of war algorithms are used to optimize the configuration of the castellage beams by using the charged sys-tem quest (Kaveh and Shakohi, 2016). [21]

Ferhaterdal and et al., 2016[22] cover a comparison of the optimally designed castellated and cellular beams using one of the search techniques. This paper also develops an improved version of HS algorithm as a robust approach to solve rectangular softened beam problems efficiently. The suggested algorithm benefits from updating certain control parameters to advantageous values on-line during the iteration process, unlike the traditional algorithm in which technique update parameters are allocated to constant values during the searching process. Using an example of an optimum size configuration of castellates and mobiles the efficiency of the IHS algorithm is numerically tested. The castellated beam with different angles, for example, creates an easier weight than that of a castellated beam with a fixed angle of 15.57%. More specifically, adjusting the angle of the hexagonal hole in the optimal construction of a cast steel beam has an important impact on optimal design, and if you are looking for a better design, it is more fitting to treat this parameter as an additional design variable.The findings from the application of IHS show that, due to their versatile geometry, cellular beams produce a cheaper solution than castellatated beams and they have many different circular hole diameters without any improvement in the manufacturing process. Konstaninos and et al., 2012 [23] found that when compared to a cellular type beam, the optimized design had increased stiffness and yield load. Several constraints, including the complexity of the web geometry as well as the analysis issues, were highlighted to routine application of topology optimisation. It is anticipated that the web opening pattern of the same architecture developed by the topology Optimisation Study would result in different depth-to-span ratios. A short section of a beam was subsequently studied for a parametric topology optimization with a view to creating a topo-logically optimized opening architecture for the wide range of beam cross sections used in use. An optimal architecture was developed for web opening.

11. Conclusion

Research to understand the performance of castellate steel beams is limited and not enough to clarify thoroughly the failure analysis and the effects on the intensity and usability of the structure of the different modes of failure. This paper therefore also contains the urgent material of today's research work and overview details in this paper better understanding and failure prediction of models for steel castellated beams:

- Castellated beam behaves satisfactorily as compared to its parent I beam in respect of deflection and strength requirement.
- Most common shapes for the opening are hexagonal, circular, octagonal, diamond, rectangular.
- Due to simplicity in fabrication mostly hexagonal and circular openings of beams are used in industries.
- Most of the research on optimization of hexagonal and circular shape is done.
- It is observed that introduction of openings in the web decreases stiffness of the beams resulting in larger deflections than the corresponding beams with solid webs.
- The strength of the beams with openings may be governed by the plastic deformations that occur due to both moment and shear at the openings.
- Failure occurs as the depth of the opening increases and also due to the stress concentration across the holes.
- The stress concentration can be alleviated to some extent by making the openings close to the neutral axis and making the cuts in a wavy manner.
- Castellated steel beam behaves satisfactory for serviceability, up to maximum depth of opening 0.6D.
- Castellated beams have holes in its web, as holes incorporated various local effects in beams, increase in load causes beams to be failed in different failure mode, which resist them to take load up to their actual carrying capacity. So, we cannot compare beams with different modes of failure directly for strength criteria.
- Castellated beam with optimum hexagonal openings is proved to be better than other opening in respect of load carrying capacity.

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