CASTELLATED BEAMS – AN OVERVIEW

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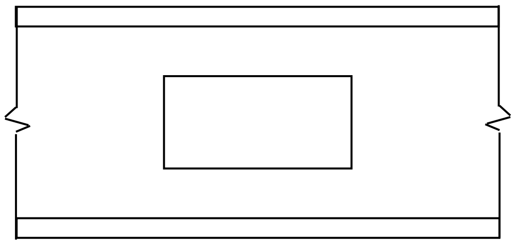
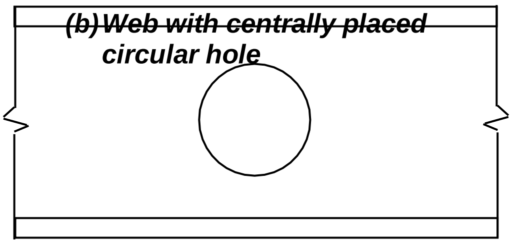
Introduction

The responsibility of Structural Engineers lies not merely in designing the structure based on ultimate safety and serviceability considerations but they also have to consider the functional requirements based on the use to which the structure is intended. While designing plant structure for heavy duty operations or a multi-storeyed building, the traditional structural steel framing consists of beams and girders with solid webs. The provision of providing passage for pipelines and air conditioning ducts are also required for satisfactory functioning for which the structure is built.

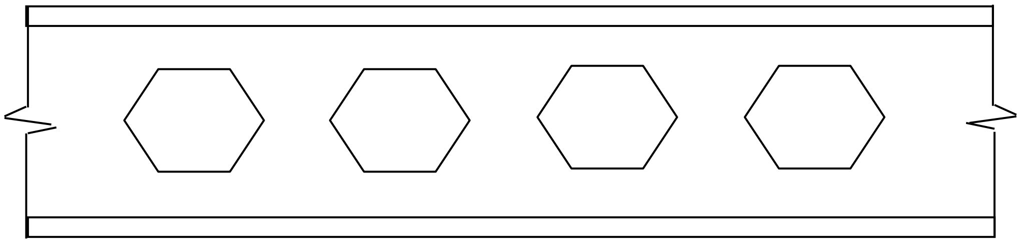
Major players in the construction industry have been constantly experimenting on ways to improve the stability of a particular building's structure. A very important innovations in the industry is the castellated beams and/or beams with web openings. Many have been capitalizing on the advantages of castellated beams to provide the different parts of structures with more support, at a much lower cost. Through innovation and continued experimentation, the castellated beam was devised, offering architectural projects with a less bulky, and more attractive appearance.



(a) Web with centrally placed rectangular hole



(b) Web with centrally placed circular hole



(c) Castellated beams

Fig. 1 Typical Beams with Web Openings

Formation of Openings / Castellations

These beams can be formed both by providing simple cuttings in the web to provide for passage of service lines in a building. These cut-outs may be rectangular or circular depending on service requirements as well aesthetic requirements. These opening can be with or without stiffeners depending on the structural strength requirements of the beams. However castellated beams are those which are formed by cutting the existing rolled sections in such a way as described in the figure below to obtain greater depth and capacity of the final section without increasing the overall weight of the beam itself. The four stages or sequences of formation of typical castellated beam is as shown below in Fig. 2. (Picture Courtesy: AISC

Journal). The final product is a castellated beam with Hexagonal castellations with increased depth compared to the original sections which ensures better section modulus and strength.

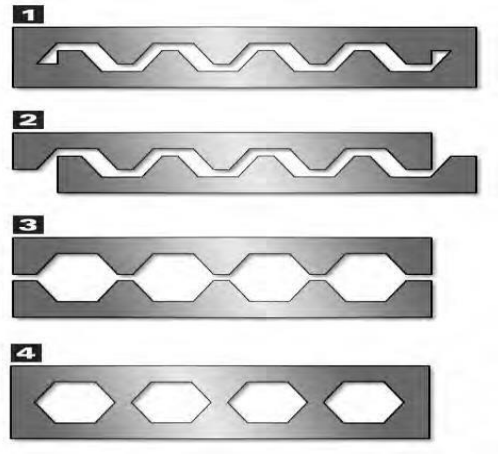


Fig. 2 Four Stages of formation of a castellated Beam

Special formations

Castellated beams offer a designer all kinds of opportunities for "cutting to size". A very unique variable depth castellated beam may be obtained by changing the cutting pattern of the initial simple straight beam as indicated in Fig. 3 below. In this way, the strength of the beam can be precisely matched to the occurring loads. That way, optimum construction can be achieved. A castellated beam that tapers in depth can quite easily be made, by setting the cutting pattern not exactly parallel to the length of the castellated beam, but at a slight angle. After cutting, one of the two halves is reversed and the two halves are then welded together lengthwise. At one end both low sides come together, at the other end both high sides. The sequence of formation of such beams are as shown in the figure below

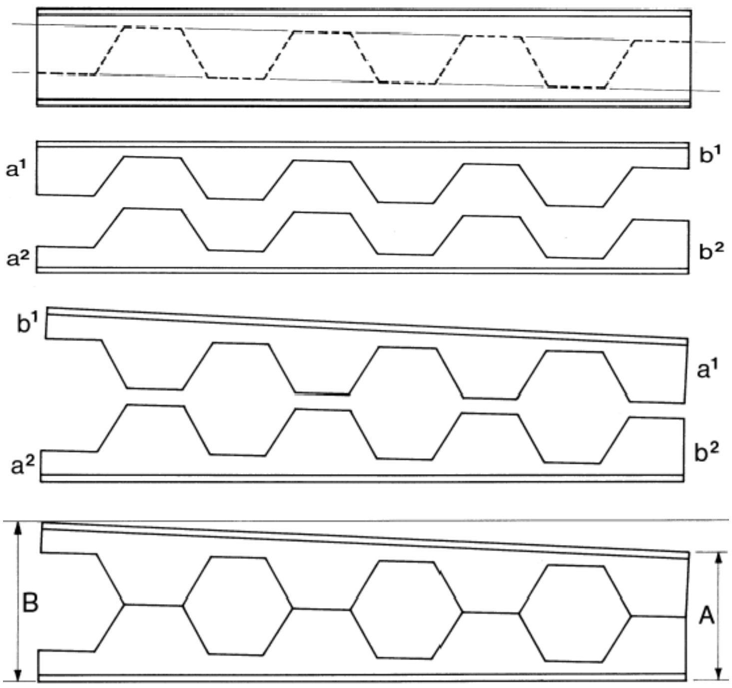


Fig. 3 Cutting Pattern to obtain Variable depth Castellated Beam

A third special possibility is the combining of a lighter upper half with a heavier lower half. Obviously, these will be cut from two separate rolled sections. As long as the number of castellated beams to be built is even, no material will be wasted. This last design is attractive, for example, when a subfloor steel beam and a concrete floor are combined. In that case studs are welded to the top flange of the castellated beam in order to ensure firm anchoring of the concrete to the beam.

Origin of Castellated Beams

The Castellated beam name is derived from the Latin word "castellatus" meaning "built like a castle having regular openings in walls like a castle." These beams were introduced to improve the depth and strength of the beam without adding more material or weight.

Due to shortage of steel immediately after WWII, engineers discovered that castellated beams were cheap to build and had an excellent strength-to-weight ratio. As a result, castellated beams have been the preferred building solution since the 1950s and were commonly used in Europe to decrease the cost of steel structures due to the low ratio of labour cost to material cost.

Properties of Castellated Beams

1. Highly efficient sections:

The principal property of castellated beams is that the depth of the beam can be increased without increasing the weight of the beam which results in increase in the load / moment capacity of the beam up to about 40% of the original section. The increase in depth also enhances the serviceability criteria like reduction in deflection of the beam. Moreover, as an alternate criterion, the permissible length of the beam for a given loading conditions can also be increased.

2. Asymmetric design:

Unique split fabrication of beam gives the ability to lower the weight of the top half of the beam, thus increasing the load-carrying capacity while minimizing the weight of the beam.

3. Other important properties:

- The design and erection of the castellated beam are elegantly simple.
- The physical characteristics of the castellated beam can be changed to achieve several goals. This beam can be customized from section to section; thus, the castellated beam is extremely versatile.
- The weight of the beam can be lowered up to 40% when compared to the wide flange steel beam

Advantages of Castellated Beams

The primary advantage of this new section is the increased depth of the beam without increasing its weight. In some instances, the depth is increased as much as 50%. By increasing the depth of the beam, strong axis bending strength and stiffness are improved as the strong axis moment of inertia, I_{xx}, and section modulus, Z_{xx}, are increased. Further, the castellations or holes also allow HVAC ductwork, plumbing pipelines, and electrical conduits to pass through them ultimately reducing the thickness of the floor assembly. However, one disadvantage is the increased fabrication costs associated with the cutting and welding of the section.

The advantages of castellated beams may be categorised as follows:

- The length of the castellated beam can be extended up to 28 metres.
- Long-span construction designs reduce the number of needed columns, resulting in a reduced number of lighter foundations.
- Castellated steel beams, can indirectly, and directly, save costs while shortening the overall construction time
- A castellated beam enhances the aesthetic appearance of a structure.
- It allows natural light into the structure.
- Castellated beam lowers the floor-to-floor height as various service lines are allowed to pass through the web openings.
- Castellated beams have a higher moment carrying capacity with no added steel
- The depth of the beam can be increased up to by 50%.
- Installation is fast and easy as the span of the beam is longer.
- Handling of the beam is easy due to the lighter weight
- The installation cost of castellated beam is 10% less compared to concrete beam
- It requires lesser maintenance
- It has a high stiffness-to-weight ratio
- Increased depth contributes to lesser vibration of the structure.
- The castellated beams are more economical, and therefore contributes to reduction in cost of the entire structure.
- The beam can be designed asymmetrically in case of increased loads.
- It can be used in composite construction with RCC and PSC slabs.

General rules for providing Castellations or Openings

The general rules to be followed while providing the openings in the web for castellated beams as well as general beams with openings are as laid down below:

- The hole should be centrally placed in the web and eccentricity of the opening should be avoided as far as possible.
- Unstiffened openings are not always appropriate, unless they are located in low shear and low bending moment regions.
- Web opening should be away from the support by at least twice the beam depth, *D* or 10% of the span (□), whichever is greater
- The best location for the opening is within the middle third of the span.
- Clear Spacing between the openings should not be less than beam depth, *D*.
- The best location for opening is where the shear force is the lowest.
- The diameter of circular openings is generally restricted to *0.5D*.
- Depth of rectangular openings should not be greater than *0.5D* and the length not greater than *1.5D* for un-stiffened openings. The clear spacing between such opening should be at least equal the longer dimension of the opening.
- The depth of the rectangular openings should not be greater than *0.6D* and the length not greater than *2D* for stiffened openings. The above rule regarding spacing applies.
- Corners of rectangular openings should be rounded.
- Point loads should not be applied at less than *D* from side of the adjacent opening.
- If stiffeners are provided at the openings, the length of the welds should be sufficient to develop the full strength of the stiffener. Various types of stiffeners are shown in Fig. 5.2(*c*).
- If the above rules are followed, the additional deflection due to each opening may be taken as 3% of the mid-span deflection of the beam without the opening.

Applications

Castellated beams are ideal choices for the following structures:

- Industrial facilities
- Parking garages
- Warehouses
- Office buildings
- Hospitals
- Schools

Major Components of a Castellated Beam

The basic structural components of the castellated beams are as shown in Fig. 4 below and these components are the ones which need to be sufficiently strong individually, to take the stress arising out of all the loads that are induced in the beams.

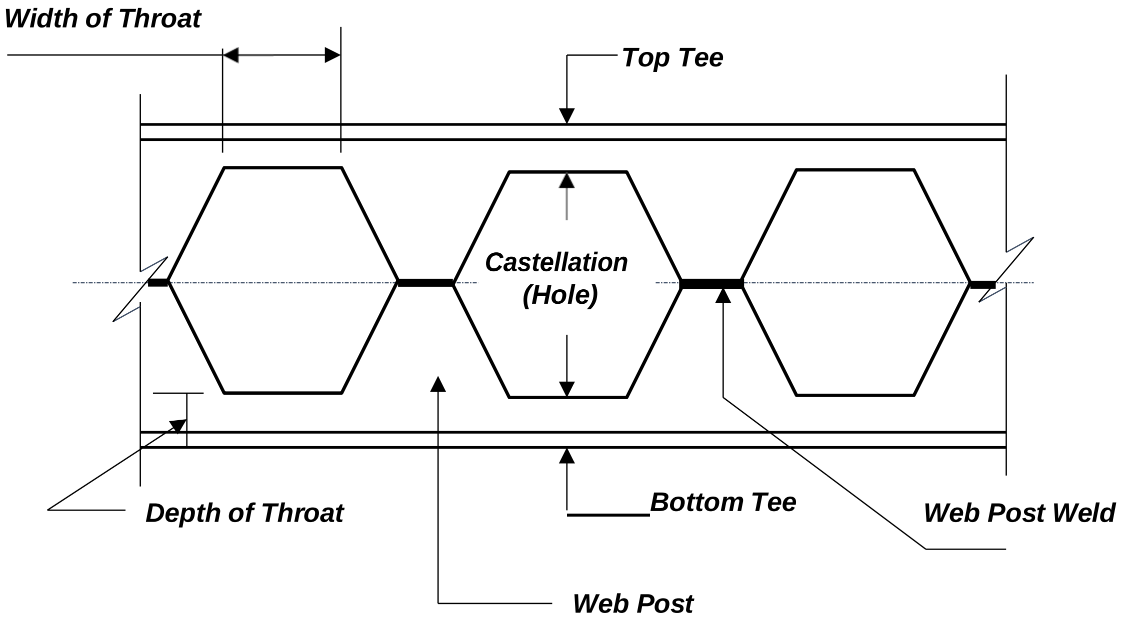


Fig. 4 Structural Components of a Castellated Beam

- **Web Post:** The cross-section of the castellated beam where the section is a solid cross-section.

- **Castellation:** The area of the castellated beam where the web has been expanded by formation of castellation (hole).

- **Throat Width:** The length of the horizontal cut on the root beam.

- **Throat Depth:** The height of the portion of the web that connects to the flanges to form the tee section.

- **Top Tee:** The Tee section formed at the top of Castellation by the Flange and web above the castellation.

- **Bottom Tee:** The inverted Tee section formed at the bottom of Castellation by the Flange and web below the castellation

Major Failure Conditions of a Castellated Beam

Design stipulations have been laid down in AISC codes and Euro codes for the design of castellated beams in details. Till date are six major modes of failure conditions in castellated beams has been observed by various research and studies.

- **Formation of a Vierendeel mechanism:**

This mode of failure is mainly due to high shear forces acting on the beam. Formation of plastic hinges at the re-entrant corners of the holes deforms the tee section above the openings to a parallelogram shape as indicated in Fig. 5 below. Beams with relatively short spans, with shallow tee sections as well as longer welding lengths are susceptible to this mode of failure. This is due to the fact that shorter span beams can carry higher loads leading to shear becoming the governing load. When a castellated beam is subjected to shear, the tee sections above and below the openings must carry the applied shear, as well as the primary and secondary moments.

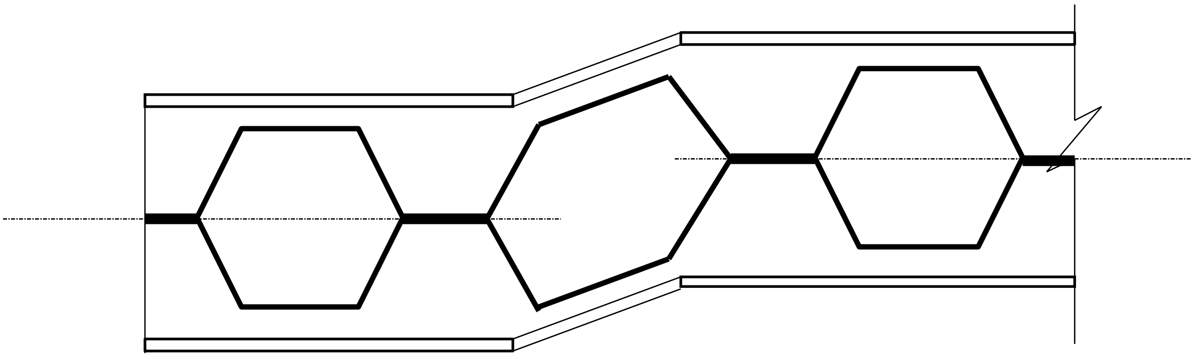


Fig. 5 Formation of Plastic Hinge

The primary moment is the conventional bending moment on the beam cross-section. The secondary moment, also known as the Vierendeel moment results from the action of shear force in the tee sections over the horizontal length of the opening. Therefore. as the horizontal length of the opening decreases, the magnitude of the secondary moment will decrease. The location of this failure will occur at the opening under greatest shearing force or if several openings are subjected to the same maximum shear, then the one with the greatest moment will be the critical one.

- **Rupture of the welded joint**

The mid depth weld joint of the web post between two openings may rupture when horizontal shear stresses exceed the yield strength of the welded joint. This mode of failure depends upon the length of the welded joints. Since the length of the welded joint is equal to the length of the opening, the reduction in the horizontal length of opening in order to reduce secondary moments may increase the vulnerability of the welded throat of the web-post.

- **Lateral-torsional buckling of the entire span**

Like standard solid web beams, out of plane movement of the beam without any distortion of the web is the manifestation of this mode of failure. This type of failure is generally associated with longer span beams with inadequate lateral support to the compression flange. Further, the reduced torsional stiffness of the web due to the provision of relatively deeper web and subsequent slender section properties, contributes to this buckling mode.

It has been found that web openings have negligible effect on the overall lateral torsional buckling behaviour of the beams. Therefore, it has been suggested from various researches, that the design procedures to determine the lateral buckling strength of solid webbed beams could be used for castellated beams, with reduced cross-sectional properties caused by slender webs

- **Lateral-torsional buckling of the web post**

The horizontal shear force in the web-post is associated with double curvature bending over the height of the post. Hence edge of the opening will be in tension and the opposite edge will be in compression and thus buckling will cause a twisting effect of the web post along its height. Several cases of web post buckling have been reported in various literatures based on actual experiments. Many analytical studies on web post buckling have also been reported to predict the web post buckling load due to shearing force.

- **Web post buckling due to compression**

If a concentrated load is applied on a point on the beam directly above a web post or if there is a reaction point directly below the web point in a castellated beam, this mode of failure may occur. This mode of failure long back in experiment on castellated beam in 1959. Buckling of the web post under large compression forces is not accornpanied by twisting of the post as it would be under shearing force. Web-post buckling is the loss of stability of the web-post caused by compression stresses due to the shear force. During this phenomenon, the web-post twists over its vertical axis, assuming the shape shown in Fig. 6a and 6b. The forces equilibrium due to shear is shown in Fig. 6c (Journal of Constructional Steel Research). Such a failure mode could be prevented if adequate web stiffeners along the periphery of the opening are provided. A strut approach to design may be undertaken, which means that standard column equations could be used to determine the strength of the web post located at a load or a reaction point.

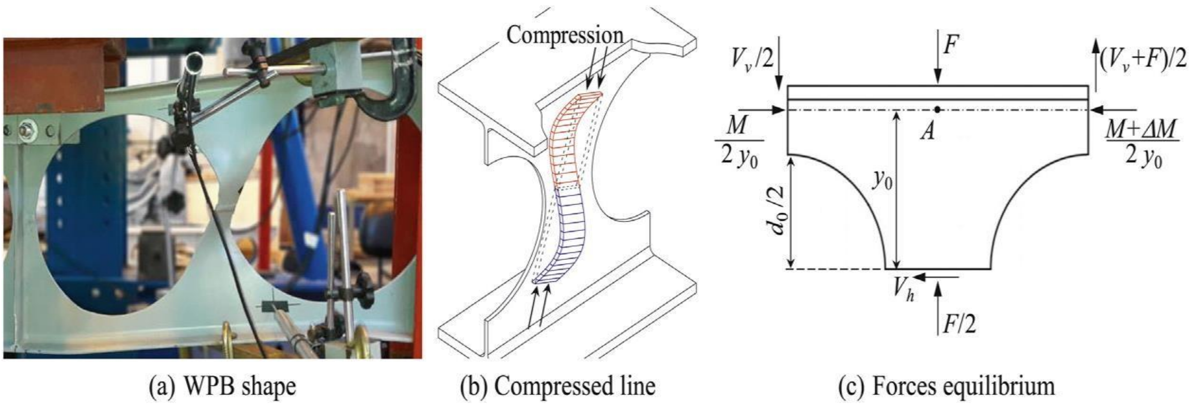


Fig. 6 Web Post Buckling under Point Load

- **Formation of a flexure mechanism.**

For compact section, under pure bending the tee sections above and below the openings yield in compression and tension until they become fully plastic. Yielding in the tee sections above and below the openings of a castellated beam was similar to that of a solid beam under pure bending forces. Thus. the maximum in-plane carrying capacity of a castellated beam under pure moment loading was determined to be $M_p = Z_p \times F$, where Z_p is the full section plastic modulus taken through the vertical centreline of the hole.

References

1. **Teaching Resources for Structural Steel Design (Volume 1,2 & 3 - Chapter 28: *"Steel Beams with Web Openings"***

   ---- Prepared jointly by:

   Indian Institute of Technology, Madras; Anna University, Chennai, Structural Engineering Research Centre, Madras, Institute for Steel Development and Growth

2. **Journal for Construction Steel Research: --**

   Article titled: ***- "Design procedure for the web-post buckling of steel cellular beams"***

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