# A Castellated Beam with and without stiffeners using ANSYS Software: A Review

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***Abstract-*** *Castellated beams have become increasingly popular in structural applications due to their enhanced load-carrying capacity and efficient use of material. These beams are created by cutting a zigzag pattern into the web of a hot-rolled steel (HRS) I-section and rejoining the cut portions, effectively increasing the beam's depth. The shape of the openings in the web can vary, with common configurations including sinusoidal, hexagonal, octagonal, diamond, and circular patterns. The increase in depth improves the beam's ability to carry loads, but it also introduces potential failure modes such as lateral-torsional buckling, shear issues, and flexural instability. To mitigate these risks, research has highlighted the importance of incorporating stiffeners into the web portion of the beam. Stiffeners, available in various forms, serve to reduce deflection, enhance strength, and minimize stress concentrations around the openings. Their strategic placement significantly improves the beam's overall structural performance and durability, making castellated beams a more reliable and efficient choice for modern construction.*

***Keywords***- Castellation, Cellular beams, Web openings, Beam modification, Castellated Beam Geometry

## I. INTRODUCTION

Numerous studies on steel structures have been conducted since the 1940s, with the aim of finding more economical solutions for construction. One such innovation was the introduction of web-opening steel beams during World War II, a method developed to reduce the cost of steel structures. Despite the high strength of structural steel, it is not always possible to fully capitalize on this strength due to the material's weight and structural constraints. To address this, various methods have been employed to strengthen steel components without adding extra weight. Web-opening steel beams, such as castellated and cellular beams, have become widely used in construction for this very reason. A significant advantage of these beams is the ability to integrate technical utilities—such as water and ventilation pipes—through the web openings, as illustrated in Figure 1.

In contrast to traditional methods, where services are placed beneath the beams, the use of web-opening beams allows for the integration of utilities within the beam itself. This approach reduces the overall building height, as there is less clear space between the ceiling and floor. The height savings can be as much as 0.5 meters per storey, leading to a more compact, economical, and efficient construction method. Moreover, the manufacturing process used to create these perforated beams has a significant impact on both the cost and structural performance of the completed building system.

These girders are typically manufactured using a specialized industrial process that involvesflame-cutting the web of an existing H- or I-shaped beam (Nseir et al., 2012).

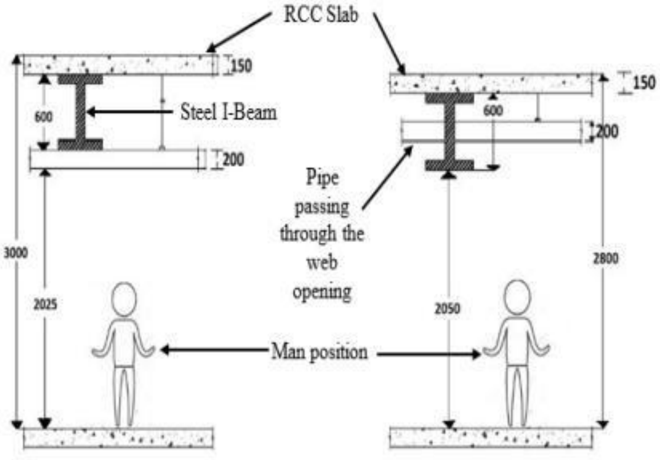

Figure1-Reductioninheightofbuildingstoreys (Morkhadeet.al.2019).

hot-rolled profile along a specific path, by welding the separated “Tees” tip-to-tip together asshownin Figure2.

Although alternatives to solid web beams, such as stub girders and trusses, exist, steel beams with web openings are often preferred. Cellular beams, in particular, have been widely used in various types of construction, including office buildings, parking garages, retail spaces, industrial halls, sports arenas, hospitals, and more. When used as floor beams, cellular beams provide long, clear spans and offer excellent flexibility for integrating services, such as utilities, into the structure.

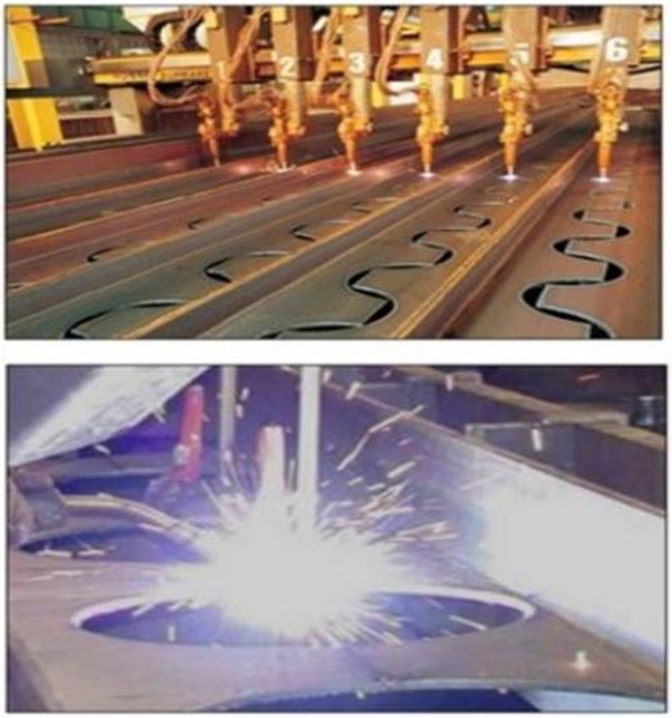

Figure2-Fabricationprocessflamecuttingofhot-rolledprofiles(Nseiret al.2012).

This paper provides a comprehensive overview of the behavior of steel beams with web openings under various failure modes. It aims to consolidate and evaluate the current body of knowledge on the subject, highlighting key issues and offering recommendations for future research directions.

## II. RESEARCH ON CASTELLATED BEAMS (BEAMS WITH HEXAGONALOPENINGS).

A beam is considered castellated if it features hexagonal openings. The term "castellatus" is derived from the Latin word meaning "to strengthen." Castellated beams, originally called "Boyd beams," were introduced to the UK market in the early 1940s. Geoffrey Murray Boyd began his research on castellated beams in 1939 (Boyd, 1939), and the fundamental construction process was described in *The Shipbuilder* in the same year. Boyd’s 1939 patent document outlined various beam shapes, which eventually became the standard design for castellated beams in the UK, as noted by Aglan et al. in 1974. Over time, different methods have been employed to analyze the elasticity of castellated beams, including difference techniques introduced by Mandel et al. in 1971 and finite element analysis detailed by Shrimani et al. in 1978. During the 1960s and 1970s, American researchers conducted experimental studies on castellated beams, proposing formulas and identifying failure modes and load-deflection behavior.

Shrimani conducted a critical study of castellated beams, focusing on various aspects such as deflection behavior, development of design load tables, determination of the optimal expansion ratio, and finite element analysis. His comprehensive research contributed to the development of the *Handbook for Castellated Beam Design*, published by Das and Srimani in 1986 (Srimani, 1977, 1980, 1981, and 1983).

The Litzka castellation method was invented by LitzkaStahlbau from Bavaria (Dougherty, 1993; Kahn, 1975; Knowles, 1991). The resulting beam, known as the *extended castellated beam* or *Litzka beam*, is characterized by octagonal apertures, as opposed to the traditional hexagonal openings. In an experimental study, Altfillisch et al. (1957) investigated the effects of changes to web-post geometry, beam depth, opening shape, and expansion ratio. The experiment included five full-scale castellated beam models. The results showed that failure occurred due to local buckling in the compression flange over the region of constant bending moment, as well as extensive yielding in the tee section.

According to Sherbourne (1966), Bazile &Texier (1968), Hussain&Speirs (1971), Hussainet al. (1973), Galambos et al. (1975), Kerdal et al. (1984), Zarrour (1995), and Redwood et al.(1998),there are seven possible failure modes connected to castellated beams.

- The flexure mechanism's formation.
- The whole beam buckling from lateral to torsional forces.
- Vierendeel mechanism formation.
- A web post's welded joint rupturing.
- An out right defiance of a web post.
- A web post's compression buckling; atee's compression buckling.

An extensive parametric study was conducted to compare the load-carrying capacity of steel beams with various sizes and shapes of web openings. Based on the results, an empirical design method was developed for steel beams with web openings of different configurations, using the generalized moment-shear interaction curve. This work presents a comprehensive overview of the design process, including worked examples (Chung et al., 2003; Liu et al., 2003).

Mohebkhah (2004) used models of castellated beams to investigate the effects of slenderness on the moment-gradient factor for simply supported castellated beams. In each case, a different equation was proposed for determining the CbC_bCb factor using modified slenderness. Additionally, Mohebkhah conducted a numerical analysis on the inelastic flexural-torsional buckling of simply supported castellated beams under pure bending with an elastic restraint. The results indicated that Winter's streamlined method should not be applied to inelastic castellated beams required to meet full-scale standards. As a result, Mohebkhah et al. (2005) derived a general formula to estimate KoptK_{opt}Kopt as a function of slenderness for all castellated beams subjected to pure bending.

Novel computational methods, including artificial neural networks (ANN), have been used to predict the failure load of castellated beams (Amayreh et al., 2005; Gholizadeh et al., 2011). It has been shown that ANN is an effective tool for predicting the failure loads of castellated beams. Furthermore, the designed network was able to accurately predict the failure load across a range of castellated beam depths, from shallow to deep.

TedahZirakian et al. (2006) attempt to investigate the distortional buckling behavior of castellated beams. The theoretical predictions of the elastic and in elastic lateral buckling loads were compared with the experimental findings.

Ellobody (2011) investigated the effects of varying beam length, steel strength, and cross-sectional geometry on castellated beams. The parametric study revealed that the failure load of thin castellated beams is significantly reduced when web distortional buckling occurs. Additionally, the study showed that using high-strength steel can notably increase the failure load of thicker castellated beams.

To predict the behavior of castellated beams, a numerical model accounting for both geometric and material non-linearity (for octagonal and hexagonal openings) was developed. A comparison of the model's results with previously collected experimental data showed a good level of agreement (Soltani et al., 2012). Showkati et al. (2012) investigated the impact of elastic bracing on buckling stability. The experimental and numerical results from this study were consistent with those of previous tests.

Kaveh and Shokohi conducted numerical research on the cost optimization of castellated and cellular beams. In their study, the cost of the beam was considered as the objective function, and the CBO (Cognitive Behavior Optimization) algorithm was used for optimization. Additionally, Kaveh et al. (2014, 2015) optimized the costs of castellated beams using a charged system search algorithm.

The optimal design for castellated beams is achieved using the tug of war algorithm. Solutions to the design problem were obtained using this algorithm (Kaveh et al., 2016a, 2016b, 2017). The design is developed in accordance with Eurocode 3 and the Steel Construction Institute's Publication Number 100. A brief introduction to the CBO algorithm is provided in Section 3.

Wang et al. (2014a, 2016) used the limited aspect approach to investigate the shear-bowing behavior of the web-post in castellated steel beams with fillet-edge hexagonal openings. The study compared the jumping behavior and web-post buckling capacity of castellated beams with hexagonal openings at the fillet edges to those with circular and elongated circular openings. Additionally, research was conducted on the large deflection behavior of castellated steel beams under fire conditions (Wang et al., 2014b).

The development proportion, internet opening measurement, internet opening form, opening up setup and also axial restriction tightness proportion of the castellated steel light beam are amongst the specifications of the beam of lights that have actually been examined.

The "Ray Technique" was used to investigate Vierendeel failure in castellated steel beams (CSBs) with fillet-edge web openings (Wang et al., 2014c). This study examined the effects of opening dimensions and shapes on the Vierendeel failure of web-perforated members. Pourbehi et al. (2015) conducted an extensive parametric study analyzing 300 castellated beam designs. Based on their research, a modified formula for determining the critical bending load of castellated beams was proposed.

Ellobody and Young (2015) investigated the nonlinear analysis and design of unprotected composite and non-composite castellated steel beams with profiled steel sheeting at elevated temperatures. Their finite element models incorporated nonlinear material properties for steel, concrete, profiled steel sheeting, longitudinal and lateral reinforcement bars, and shear connection behavior at both room and high temperatures. The study concluded that, for most unprotected composite and non-composite castellated steel beams, the EC4 design code is conservative. Yuan et al. (2016) conducted an analytical study to determine the deflection of a castellated beam under a uniformly distributed load. Their findings provided a method for calculating deflection based on the minimum potential energy principle. The analytical results were found to closely match the finite element results. Morkhade et al. (2018) performed a comparative analysis of the ultimate load capacity of castellated beams with varying expansion ratios and beams without web openings. More recently, Morkhade et al. (2019) used finite element analysis and ANSYS to study the flexural response of hybrid beams with different opening shapes, including square, rectangular, circular, and hexagonal.

## III. RESEARCH ON CELLULAR BEAMS (BEAMS WITH CIRCULARANDSINUSOIDALOPENINGS).

As shown in Figure 3, a cellular beam is formed by cutting a hot-rolled steel profile along a predetermined path and then welding the two chords together, resulting in a beam with uniformly spaced apertures of identical shape. This type of beam offers several advantages:

- The castellated beam has a greater height than the original profile, resulting in a higher second moment of area. This allows for larger spans with the same amount of steel. The aesthetic appeal of the beam is often significant and can be showcased in the structure.
- Cellular beams allow ducts and other services to pass through their openings, leading to a significant reduction in floor depth.

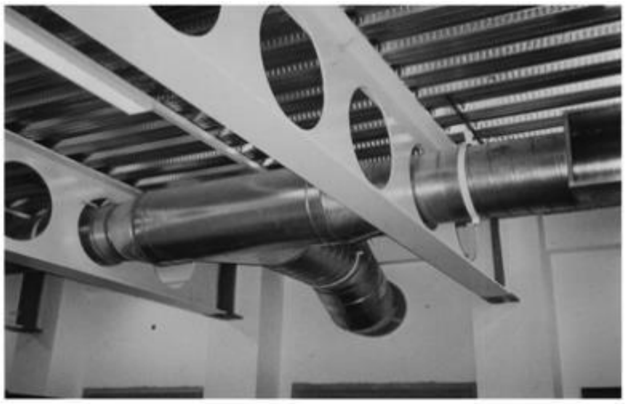

Figure3-Placementofservicesthroughwebopenings (Chunget.al.2001)

Chung et al. conducted an analytical study that considered the location of openings in cellular beams. Both geometric and material non-linearity were incorporated into the finite element model. The paper presents the load-carrying capacity of the cellular beam and, for the practical design of steel beams with circular web openings, recommends an empirical shear-moment interaction curve at the perforated section to address the Vierendeel mechanism (Chung et al., 2001).

Sweedam (2011) developed a simplified method for accurately predicting the moment modification factor KLBfor cellular beams. A three-dimensional finite element model was created for an I-shaped cellular beam, considering a broad cross-sectional dimension, span, and web perforation. Tsavdaridic and D'Mello (2012) studied the impact of web opening depth and spacing on the behavior of web posts. This paper explores the effective "strut" action in web-post buckling and proposes an empirical formula to predict the strength and ultimate vertical shear load of web posts based on the shape of their web openings.

Using the finite element approach, Panedpojaman and Thepchatri (2013) explored the deflection behavior of cellular beams. The numerical study included 408 cellular beam models, with variables such as opening size, opening spacing, beam length, and cross-sectional dimensions. The authors proposed a coefficient function that can be used to predict the bending behavior of cellular beams.

Panedpojaman (2014) proposed design formulas for the shear strength of local web-post buckling in both composite and non-composite cellular beams. To investigate the buckling behavior, a finite element model of the web-post was used in a parametric study to develop the design approach. According to Panedpojaman et al. (2014), these new design formulas make it easier to design cellular beams both safely and economically. Sonck et al. (2015) studied the side torsional buckling resistance of cellular beams. Based on the findings of their parametric study, they proposed an initial design method. This approach is based on the European standards currently used for determining the side torsional buckling resistance of I-section beams, but it modifies the buckling curve and adjusts the cross-sectional property calculations.

Morkhade and Gupta conducted experimental research on the behavior of steel beams with circular web openings by adjusting the spacing-to-size ratio and the types of web openings (Morkhade et al., 2015a, 2017). The key finding of the study was that the minimum limit of 1.08, as specified by BS 5950 for the S/Do ratio, is crucial. It was observed that S/Do ratios of 1.33 and 1.5 were relatively effective. The circular web openings proved to be highly efficient, as they were easy to fabricate and showed lower stress concentrations at the web openings.

Nadjai et al. (2016) studied the performance of both protected and unprotected cellular beams under fire conditions. In this study, the behavior of full-scale composite floor systems with both protected and unprotected cellular steel beams, featuring intumescent coatings with varying sizes and shapes of openings, was experimentally tested at high temperatures. The study concluded that the most effective material for fire protection of steel cellular beams is intumescent coating.

Panedpojaman conducted a detailed parametric study by analyzing 846 nonlinear finite element (FE) simulations to investigate the inelastic side torsional buckling resistance of cellular beams and compare it with the EC3 standard design. According to Panedpojaman et al. (2016), the parameters considered in the FE simulations included load arrangements, section ratios, opening ratios, spacing ratios, and non-dimensional slenderness—all of which were within practical limits for cellular beams.

Martin proposed a new approach for designing cellular beams with balanced wave openings. The researchers identified two key factors that typically influence the ultimate design of these beams: the beam's ability to resist Vierendeel bending and its capacity to withstand the transverse shear forces in the web posts. Furthermore, because cellular beams are often created by bending the posts, it was concluded that cellular beams with balanced openings are not susceptible to the same failure modes as those with circular openings (Martin et al., 2017).

Elsawaf and Hassan (2018) conducted two fire tests to validate and provide detailed simulation results on the behavior of perforated beams in fire conditions. The study examined seven distinct shapes of web openings. Factors considered in the analysis included the size and shape of the openings, load ratio, and the level of axial restraint. The results showed that the best performance for perforated beams under axial restraint in fire conditions was achieved with circular and hexagonal web opening shapes.

Zaher (2018) analyzed the behavior of perforated cellular arched I-beams with hinged supports under a concentrated vertical load applied at midspan. The paper discusses the experimental setup, material properties, and boundary conditions. The study experimentally investigated how arched cellular beams behaved under fixed, concentrated loads. In addition to recording the stresses around the openings, the deflection and lateral displacements of the web were observed. The failure modes and experimental measurements are presented in this paper. Morkhade et al. (2019) explored the strength behavior of web beams with circular web openings and trapezoidal grooves. They found that the ultimate load capacity of these beams was significantly affected by the groove angle. The authors also examined the effects of openings on the ductility and ultimate load behavior of steel beams with circular web openings, both experimentally and mathematically (Morkhade et al., 2015c, 2019).

## IV. CONCLUSION

There is still limited research that fully explains the failure analysis and the impact of various failure modes on the strength and serviceability of castellated steel beams. As research on the performance of these beams remains scarce, enhancing the understanding and predictive capabilities regarding the failure of castellated steel beam models continues to be a critical area of ongoing study. This paper compiles the existing knowledge and insights on the topic.

1. It has been observed that, in addition to geometric characteristics, the response of a castellated steel beam is influenced by factors such as span length, material strength, and the number, shape, and location of the holes.
2. It has been determined that further research is needed to fully understand how a castellated steel beam responds to different stress conditions. Additionally, the analysis and design of castellated beams should incorporate stiffeners in the transverse direction to minimize web post buckling.

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