eJSE International
Electronic Journal of Structural Engineering 19(1) 2019

# Behavior of Castellated Steel Beams: State of the Art Review

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ABSTRACT: The state of the art of behaviour of Steel Castellated Beams is explain in this paper. The present research status of behavior of castellated beams is not mature and need much through study compared to beams without openings in the web. The existence of various shapes of openings such as circular, hexagonal, rectangular, octagonal and oval etc. in beams web add some additional failure modes namely; lateral-torsional buckling of web posts, web post buckling due to shear force, formation of four plastic hinges around the corners of openings, rupture of welded of joints in the castellated beams over a conventional steel beams. A review of experimental and analytical work carried out on castellated steel beams has been presented. The paper also focuses on the influence of various parameters such as types of openings, size of openings, spacing of the openings, aspect ratio, various numbers of openings and strengthening on the behavior of steel beams with web openings.

KEYWORDS: Castellated steel beam, Conventional beam, Lateral-torsional buckling, Vierendeel mechanism, State of the art review.

## 1 INTRODUTION

Since 1940 studies have been conducted by several researchers to discover advance means to achieve the economy in steel structures. Steel beams with web openings was firstly used in structures during World War II to decrease the cost of steel structures. The high strength properties of structural steel cannot continually be used to the greatest advantage. Consequently, numerous different techniques have increased the stiffness of steel elements without growing the weight of the steel. Hence, steel beams with web openings such as castellated and cellular beams have been used widely. Integration of technical utilities, such as water and ventilation pipes through the web openings of the beam as revealed in Figure 1 is a most important advantage in steel buildings.

This reduces the height of the building as the clear space between the ceiling and the floor reduces as compared with the conventional method wherein the services are placed below the beams. Savings in such terms could be up to 0.5 m per storey. The consequence of this is a more justifiable, compact and cost-effective method of construction. The manufacturing method of the above-mentioned perforated beams is a very important factor as it affects the cost and the structural behaviour of the final construction system. Such girders are usually fabricated through a specific industrial process (Nseir et al. 2012), by means of flame-cutting to the web of an existing H or I-shaped

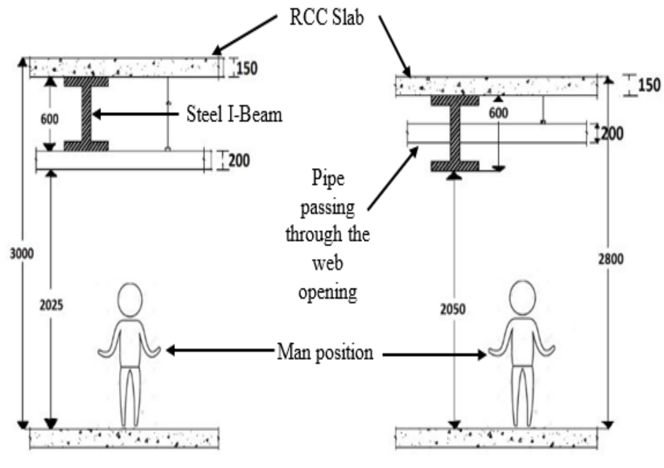


Figure 1 - Reduction in height of building storeys (Morkhade et. al. 2019).

hot-rolled profile along a specific path, by welding the separated "Tees" tip-to-tip together as shown in Figure2.

Steel beams with web openings can commonly use, even though other substitutes to solid web beams such as stub girders, trusses etc. are available. Cellular beams have been used in office buildings, car parking structures, shopping centers, industrial halls, sports halls, hospitals etc. This provide long clear spans and great flexibility for service incorporation, when they are used as floor beams.

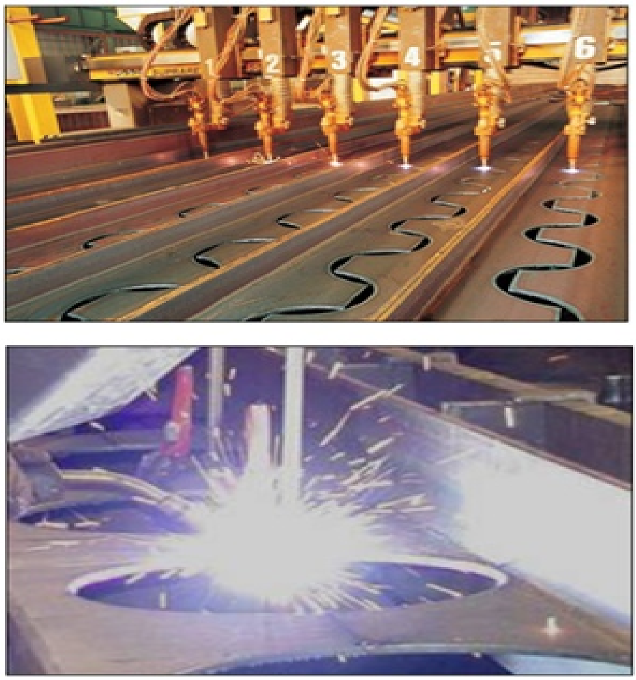

Figure 2 - Fabrication process flame cutting of hot-rolled profiles (Nseir et al. 2012).

The state of art knowledge on the behaviour of steel beams with web openings subjected to various failure modes is presented in this paper. This paper attempts to collect and critically examine the state of current knowledge in the field of steel beams with web openings; presents the existing problem and suggests the scope for further research work.

## 2 RESEARCH ON CASTELLATED BEAMS (BEAMS WITH HEXAGONAL OPENINGS).

A beam with hexagonal openings is called as castellated beam. The castellatus means *to fortify (To Strengthen).* Castellated beams initially known as the “Boyd beam”, these products were first marketed in the UK in the early 1940s. The study of castellated beams was started by Geoffrey Murray Boyd in 1939 (Boyd, 1939). The basis of the beam’s method of construction, described by a writer in The Shipbuilder (1939). Patent specification (Boyd, 1939) discussed various geometries of the castellation, and the beam type was later adopted as the standard castellated beam geometry in the UK (Aglan et al., 1974). Elastic analysis of a castellated beam has been carried out by a number of methods which include finite difference (Mandel et al., 1971) and finite element analysis (Shrimani et al., 1978). Researchers from U.S.A. performed tests on castellated beams during the 1960s and 70s. The researchers also suggested many empirical formulas, identified the failure mode shapes and load deflection behavior.

Srimani conducted a critical study of castellated beams. Study consisted of finite element analysis of castellated beams, development of design load tables, optimum expansion ratio and investigation of deflection in castellated beam. Das and Srimani (1986) also published the handbook for the design of castellated beams (Srimani, 1977, 1980, 1981 and 1983).

The Litzka castellation process was developed by Litzka Stahlbau of Bavaria (Dougherty 1993, Kahn 1975, Knowles1991). The end product is characterized by octagonal openings rather than hexagonal openings and is known as the Litzka beam or the extended castellated beam. Altfillisch et al. conducted an experimental study by varying expansion ratio, beam depth, opening and web-post geometry. The experimental test consisted of five full scale models of castellated beam. Results showed that beam failed through extensive yielding of the tee section and local compression flange buckling in the region of constant moment (Altfillisch et al., 1957).
Seven potential failure modes are associated with castellated beams as follows (Sherbourne, 1966, Bazile & Texier, 1968, Hussain & Speirs, 1971, Hussain et al., 1973, Galambos et al.1975, Kerdal et. al., 1984, Zarrour, 1995, Redwood et al., 1998).

- Formation of a flexure mechanism.
- Lateral–torsional buckling of the entire beam.
- Formation of Vierendeel mechanism.
- Rupture of the welded joint in a web post.
- Shear bucking of a web post.
- Compression buckling of a web post.
- Compression buckling of a tee.

A comprehensive parametric study was carried out to investigate and compare the load carrying capacity of steel beam with web openings of various sizes and shapes. An empirical design method for steel beam with web openings of various sizes and shapes was developed through the use of generalised moment-shear interaction curve. The complete design method is fully presented in this paper provided with worked examples (Chung et al.,2003, Liu et al. 2003).
Mohebkhah used castellated beam models to study the effect of slenderness on moment-gradient factor of simply supported castellated beams (Mohebkhah,

2004). An alternative equation has been suggested for evaluating the $C_b$ factor for each case in terms of modified slenderness. Mohebkhah also performed the numerical study on the inelastic flexural-torsional buckling of simply supported castellated beam with an elastic restraint under pure bending. The results showed that Winter's simplified method to determine full scale requirements should not be applied to inelastic castellated beams. Therefore a general equation was proposed to determine the value of optimum stiffness ($K_{opt}$) in terms of beams slenderness, applicable to all castellated beams under pure bending (Mohebkhah et al.,2005).

The use of new computational technique Artificial Neural Networks (ANN) is used in predicting the failure load of castellated beams (Amayreh et al., 2005, Gholizadeh et al., 2011). It has been shown that ANN can effectively be used to predict the failure loads of castellated beams. It has also been shown that the designed network predicted the outputs with acceptable accuracy, covering the range from shallow to larger depth of castellated beams.

An attempt is made to study the distortional buckling behaviour of castellated beams (Tedah Zirakian et al.,2006). Comparison was made between the experimental results and the theoretical predictions of the elastic and inelastic lateral buckling loads. Ellobody studied the effects of change in cross-sectional geometries, beam length and steel strength (Ellobody,2011). The parametric study showed that the presence of web distortional buckling causes a considerable decrease in the failure load of the slender castellated beams. It is also shown that the uses of high strength steel an offer a considerable increase in the failure load of less slender castellated beams.

A numerical model is developed taking into account both material and geometric non-linearity to predict the behaviour of castellated beams (Octagonal and hexagonal openings). The results obtained in the study was compared with the experimental data obtained previously and have shown good agreement (Soltani et al., 2012). The effect of elastic bracing on buckling stability has been studied by Showkati. The experimental findings and results of this study were found to be consistent with those of the other test as well as numerical investigation (Showkati et al., 2012).

Kaveh and Shokohi performed numerical investigatation associated with the cost optimization of castellated beams and cellular beams. The CBO algorithm was utilized for optimization and cost of the beam is considered as the objective function. Cost optimization of castellated beams using charged system search algorithm (Kaveh et. al; 2014, 2015).

The *tug of war algorithm* is applied to optimal design of castellated beams. The same algorithm was used for obtaining the solution of design problems (Kaveh et. al; 2016a, 2016b, 2017). Optimum design of castellated beams is formulated based on the Steel Construction Institute Publication Number 100 and Euro Code 3. In Section 3, the CBO algorithm is briefly introduced

The shear buckling behavior of the web-post in a castellated steel beams with fillet corner hexagonal web openings has been studied by Wang et al., using the finite element method (2014a, 2016). The buckling modes and buckling capacity of the web-post in the castellated beams with fillet corner hexagonal web openings are compared with those having circular and elongated circular openings. The large deflection behaviors of restrained castellated steel beams in fire has also been studied (Wang et al., 2014b). The studied parameters of the castellated steel beams includes the expansion ratio, web opening dimension, web opening shape, opening arrangement, and the axial restraint stiffness ratio of the castellated steel beam.

Vierendeel failure of castellated steel beams (CSBs) with fillet corner web openings is investigated by using Finite Element Method (Wang et al., 2014c). Effects of opening dimensions and opening shapes on the Vierendeel failure of web-perforated members are investigated in this paper. An extensive parametric study has been carried out by Pourbehi et al. (2015) to study 300 models of castellated beam. Based on the study a modified formulation was proposed to estimate the critical buckling load of castellated beams.

Ellobody and Young (2015) studied the nonlinear analysis and design of unprotected composite and non-composite castellated steel beams with profiled steel sheeting at elevated temperatures. The variables in Ellobody study was the nonlinear material properties of steel, concrete, profiled steel sheeting, longitudinal and lateral reinforcement bars as well as shear connection behaviour at ambient and elevated temperatures were considered in the finite element models. The study show that the EC4 is conservative for most of the unprotected composite and non-composite castellated steel beams. To determine the deflection of castellated beam due to uniformly distributed load an analytical study has been performed by Yuan (Yuan et al., 2016). The results from the study suggested the solution to calculate de-

flection using the principle of minimum potential energy. Close agreement was found between the finite element results and the analytical solution.
Comparative study of ultimate load for castellated beams and beams with no web opening was carried out by varying the expansion ratio of castellated beam (Morkhade et.al; 2018). Recently, analytical investigation has been conducted by using finite element method using ANSYS, to study the flexural response of hybrid beams. The shape of openings considered in this study were hexagonal, circular, square and rectangular (Morkhade et. al; 2019).

## 3 RESEARCH ON CELLULAR BEAMS (BEAMS WITH CIRCULAR AND SINUSOIDAL OPENINGS).

A cellular beam is made by cutting a hot rolled steel profile following a specific path, and welding of the two chords, which forms a beam with regularly spaced openings having identical shapes as depicted in Figure3. This type of beam has several advantages:

- Cellular beams allow ducts and services to pass through their openings, and then lead to a substantial reduction of the floor thickness;
- The final beam has a greater height than the basic profile and thus a greater second moment of area: it is then possible, for the same steel weight, to achieve larger spans;
- The aesthetic aspect is generally of major interest and can be expressed in the structure.

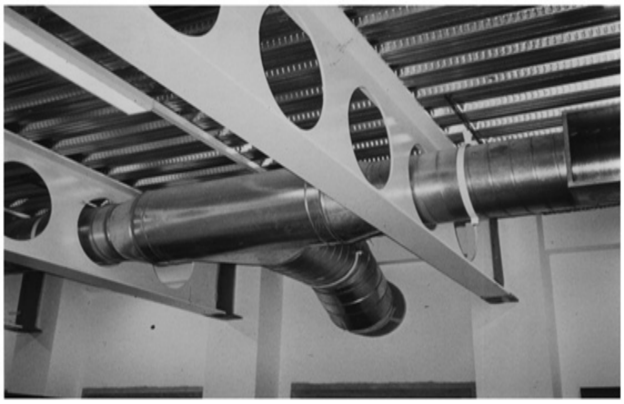

Figure 3 - Placement of services through web openings (Chung et. al.2001)

Chung et al. carried out the analytical study considering location of openings. The finite element model was prepared considering both geometric and material non-linearity. In this paper the load carrying capacity of cellular beam has been presented. An empirical shear-moment interaction curve at the perforated section is suggested for practical design of steel beams with circular web opening against vierendeel mechanism (Chung et al.,2001).
A simplified approach was developed to enable accurate prediction of a moment modification factor $K_{LB}$ for cellular beam by Sweedam (Sweedam, 2011). Three-dimensional finite element model of I-shaped cellular beam was developed with a broad cross-sectional dimension, span and web perforation. Tsavdaridic and D'Mello (Tsavdaridic et al., 2012) performed the study for effect of web opening spacing and web opening depth of web-posts. In this paper an attempt has been made to investigate the effective 'strut' action of the web-post buckling and propose an empirical formula which predicts the ultimate vertical shear load, strength of web-posts from the particular web opening shapes.

Panedpojaman and Thepchatri (Panedpojaman et al., 2013) studied the deflection behaviour by using finite element method. The numerical analysis consists of 408 models of cellular beam. The variable in the study are cross-section dimension, beam slenderness, opening size and opening spacing. From the study performed the authors suggested a coefficient function which can be used to predict the deflection of cellular beams as follows,

$$\partial_{\max} = \frac{1}{c} \text{x} \frac{5wL^4}{384EI_{net}} \quad (1)$$

Panedpojaman proposed design equations for the shear strength of local web-post buckling in non-composite symmetric or asymmetric cellular beams. To develop the design method, a finite element model of the web-post is used to investigate buckling behavior and mechanism in the parametric study. The new design equations facilitate safe and cost-effective design of cellular beams (Panedpojaman et al., 2014).
Sonck studied the lateral torsional buckling resistance of cellular beams (Sonck et al., 2015). Using the results of the parametric study, a preliminary design approach was proposed by the authors. This approach is based on the currently existing European guidelines for the calculation of the lateral torsional buckling resistance of I-section beams, but with a modified calculation of the cross-sectional properties and a modified buckling curve selection.

Morkhade and Gupta conducted experimental research the behaviour steel beam with circular web openings by varying spacing to diameter ratio and types of web openings (Morkhade et al., 2015a, 2017). The main finding of the study was that, the minimum limit given by BS 5950 on S/Do is 1.08

which was found to be critical. The S/Do ratios of 1.33 and 1.5 were found to be very effective. The circular web openings were found to be very effective as it showed less stress concentration at the web openings and was easy to fabricate.

The Performance of unprotected and protected cellular beams in fire conditions has been examined by Nadjai et al. (Nadjai et al., 2016). In this paper the authors performed an experimental study at elevated temperatures on the behaviour of full-scale composite floor unprotected and protected cellular steel beams with intumescent coating having different size and openings shape. The finding from this paper is that intumescent coating is the most effective fire protection material for steel cellular beams.

Panedpojaman carried out an extensive parametric study by analyzing the 846 nonlinear finite element (FE) simulations to investigate the inelastic lateral torsional buckling resistance and to compare with the EC3 standard design. The parameters in FE simulations were loading configurations, section ratios, opening ratios, spacing ratios, and non-dimensional slenderness, in the ranges that are practical in cellular beams (Panedpojaman et al., 2016).

A new method for the design of cellular beams with sinusoidal openings has been proposed by Martin. The researchers also suggested that, two criteria generally influence the final design for this type of cellular beams: the resistance of the beam to Vierendeel bending and the resistance to the horizontal shear force of web-posts. It is also concluded that cellular beams with sinusoidal openings are not sensitive to the same failure modes as cellular beams with circular openings, as cellular beams are often designed by the buckling of posts (Martin et al., 2017).

Two fire tests were conducted for validation and detailed simulation results of fire test of the behavior of perforated beam in fire (Elsawaf and Hassan, 2018). In this test the authors reported the seven web openings of different shapes. The parameters considered were the opening shape, size, applied load ratio and the level of axial restraint. From this investigation it is found that the circular and hexagonal web opening shapes gives the best behavior of axial restraint perforated beams in fire.

Zaher investigated the perforated cellular arched I-sections with hinged-hinged supports under a mid-span vertical concentrated load. Manufacturing, material properties, boundary conditions, and the test setup are discussed in this paper. Experimentally studied the behaviour of arched cellular beams under static concentrated loads. The deflection and web lateral displacements were monitored, and the strains around the holes were recorded. This paper presents the failure modes and the experimental measurements. (Zaher, 2018). The strength behaviour of trapezoidally corrugated web beam with circular web openings has been studied by Morkhade et. al., (2019). It is found that web corrugation angle play an important role in ultimate load behaviour of such type of beams. The authors also studied the effect of openings on ductility of beams as well an ultimate load behaviour of steel beam with circular web openings experimentally as well as numerically (Morkhade et al. 2015c, 2019)

## 4 RESEARCH ON BEAMS WITH SQUARE AND RECTANGULAR OPENING.

Thevendran and Shanmugan have conducted experimental and numerical research on beams with rectangular openings (1991). Also studied the number of openings, their size and locations. The theoretical outcomes attained by using energy method are related with experimental outcomes. Fahmy (1996) carried out study of composite beams having rectangular holes in the web. A new technique has been suggested for maximum load deflection response of castellated composite beams having no stiffeners. The suggested technique described about the involvement of the reinforced concrete slab to the shear strength of the composite beam. The openings considered in the study may be concentric or eccentric with respect to the steel section.

Shanmugam et al. (2000) studied the effect of shape of openings, web slenderness, flange stiffness and developed a comparison between analytical results with the available experimental results for yielding patterns, ultimate load values and load-deflection relationships. The comparison showed a good agreement between the finite element and experimental results. This paper monitors the behaviour of plate girders containing web openings.

Zhou et al. (2012) studied the numerical method to verify the accuracy of the analytical methods, a numerical model of perforated beam is developed using ANSYS. Authors also evaluated two analytical methods for determining the elastic deflection of I-beam containing rectangular web opening. Results of the two analytical methods showed good agreement with finite element method both in the perforated region and unperforated region.

Chung and Lawson (2001) conducted an analytical research on beam with rectangular openings. Critical observation has been made on sizing of opening as a function of the utilization of the shear and bending resistance of composite beams. Also examined the structural behavior of the perforated composite beam with deformable shear connectors of different deformation characteristics. A design method for composite beams with large web opening is presented w.r.to.Eurocode 4. A comprehensive parametric study was carried out (Chung et al; 2003) to investigate and compare the load carrying capacity of steel beam with web openings of various sizes & shapes. An empirical design method for steel beam with web openings of various sizes and shapes was developed through the use of generalised moment-shear interaction curve.

Morkhade & Gupta had conducted analysis of steel I-beams with rectangular web openings (2015b). The objective of the analysis was to investigate the effect of size of openings, depth of openings and corner radius of rectangular openings on ultimate load behavior of beams with web openings. The experimental study consists of testing of three different shear openings sizes and compared solid deep beams and deep beams with shear openings and predicting the fracture load, behavior of beams, crack pattern and stresses of the proposed reinforcement configurations (Ibrahim et.al; 2018). This paper deals with the model of various boundary conditions, unusual geometry and different load cases.

The experimental test and FE analysis used to determine the ideal shape of web opening (WO) shear connector for a slim floor system (Hosseinpour; 2018). Analysis investigated the ultimate shear strength, failure mode and ductility performance of steel beams with square openings. The author found that a square shaped opening improved the shear resistance of web opening (WO) connectors, and higher compressive and tensile strength of the infill concrete resulted in higher shear strength. The test results showed that, shear strength of the square (WSO) shear connector was high compared with rectangular (WRO) and circular (WCO).

The web opening sizes led to large degrees of flexural weakening, with reductions in the beam flexural capacity up to 47%. The FRP strengthening system is needed to avoid shear failure of the beam and confine the web chord created by the opening to ensure a ductile response. In this paper a total of eight full-scale RC beams has been analyzed, including one rectangular beam and seven T-section beams. The proposed FRP strengthening system, enhances the shear capacity of the beam, and also significantly improves the ductility of the failure process Nie (2017).

Morkhade and Gupta made an attempt to study the dynamic behaviour of steel beam with rectangular openings. The study reveals that shape and size of openings, reinforcement severely affects the time period and frequency of beams. The authors also studied the effect of position of opening on the buckling load of beams with square and rectangular openings. (Morkhade et al, 2015d, 2018).

Salama and Kas studied seven beam specimens and the behavior of T shaped RC beams with rectangular web opening under pure torsion. The investigated parameters were flange width, flange thickness, opening height. The effects of the studied parameters on the cracking torque, the ultimate torque, the angle of rotation at cracking, the angle of rotation at ultimate, and failure modes. A new analytical model based on new softened truss model has been used for predicting the torsional behavior of the tested beams. The results found that increasing the flange width or thickness increases the torsional capacity and angle of rotation at different levels due to stiffness Enhancement (Salama and Kas; 2018). The experimental study of rectangular beams with stiffened large web openings with different dimension and configuration of stiffeners has been reported (Dafafea et.al; 2019).

## 5 CONCLUDING REMARKS

Research that has been carried out to understand the performance of castellated steel beams are limited and was not sufficient to fully explain the failure analysis and consequences of various modes of failure on strength and serviceability of the structure. Therefore, better understanding and failure prediction of models for steel castellated beam is still the urgent essence of today’s research works and information available is summarized in this paper, as follows

1. A summary includes the response of castellated steel beam with emphasis on different parameters such as failure modes, methods of analysis and general design recommendations.
2. It has been seen that the beside the geometrical properties, the span length, material strength, number, shape and the location of the hole affect the response of castellated steel beam.
3. It is concluded that extensive research is required to understand the response

castellated steel beam under different loading conditions.

## 6 RESEARCH GAP & RECOMMENDATION FOR FUTURE WORK

1. Numbers of studies are available for castellated beams with limited work on cellular beams. Therefore Codes and design guidelines are creating a demand for analysis techniques for steel beams with web opening to avoid different types of failures.
2. Need to study the response of castellated beams to fire.
3. The further work on this topic can be extended to study the behaviour trapezoidally corrugated beam with web openings.

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