The Egyptian International Journal of Engineering Sciences and Technology

ISSN: 1687-1006 p
ISSN: 2682-3640 e

https://eijest.journals.ekb.eg/

Vol. 49 (2025) 28–40

DOI: 10.21608/EIJEST.2024.290626.1275

Comparative Study of Castellated Steel Beams with Varying Compactness Ratios and different stiffener configurations

Nehal M. Ayash [a*], Fattouh M. F. Shaker [b], Amr Gamal Fouad [c], Mahmoud Shahat [d]

[a] *Associate Professor, Civil Engineering Department, Faculty of Engineering at Mataria, Helwan University, Cairo*
[b] *Professor of Steel Structures and bridges, Civil Engineering Department, Faculty of Engineering at Mataria, Helwan University, Cairo*
[c] *Graduate student, Civil Engineering Department, Faculty of Engineering at Mataria, Helwan University, Cairo*
[d] *Assistant Professor, Civil Engineering Department, Faculty of Engineering at Mataria, Helwan University, Cairo*

ARTICLE INFO

Article history:

Received 18 May 2024
Received in revised form 14 July 2024
Accepted 14 July 2024
Available online 14 July 2024

Keywords:

1st Castellated Steel Beams
2nd Compactness cases
3th stiffener patterns
4th web post buckling
5th ANSYS

ABSTRACT

Because castellated beams have many benefits in both engineering and economics, their application is growing daily. Space and lightweight are always important considerations, in addition to saving space by allowing large pipes, ducts, etc. to pass through the opening, utilizing of a castellated beam will help lessening the weight of the steel. However, these holes could severely limit the beam's ability to support loads, putting the beam in danger. Stiffeners surrounding the openings can increase strength of the castellated beam, making it more structurally capable. Therefore, a nonlinear numerical analysis is carried out in this study using ANSYS to study the effect of change in compactness for castellated beams, and the effect of various stiffener patterns (boundary, sleeve, horizontal, and vertical) on ultimate load of various compactness castellated beams to assess the effectiveness of the stiffeners placed around the openings. The findings demonstrated that beams with compact sections proved to be more successful to be castellated than beams with non-compact and slender sections. Since the load capacity of slender castellated beams increases by 50% and 43% when stiffened by vertical, boundary, or sleeve stiffeners, respectively. Stiffening the slender castellated beams is more effective than non-compact ones. It is inefficient to stiffen compact castellated beams since doing so adds weight even while it increases load capacity by 10%. For cases of slender and non-compact specimens, the failure mode altered from web post buckling (W.P.B.) to flexural failure when stiffened by the boundary or sleeve stiffeners. Nevertheless, the horizontal stiffeners are unable to change the mode of failure.

1. Introduction

Steel cellular beams are becoming more and more popular due to their benefits in terms of price and appearance. Castellated beams are utilized to strengthen and deepen beams without adding more weight or material. They contain a repeating pattern of regular hexagonal perforations across their web. These beams, which are often constructed from hot-rolled steel I-sections, have regular perforations all the way along their length because their webs were chopped and welded to make deeper members (see **Figure (1)**).

Cellular beams have significantly more complex structural behaviour under flexure than parent I-shaped beams. In terms of structural performance and moment-carrying capability, castellated beams are superior to parent I sections. Furthermore, their application for wide spans enhances their aesthetic appeal and accentuates architectural elements. It also gives MEP (mechanical, electrical, and plumbing) lines access to pass through the web aperture. Castellated beams were most used in parking garage construction because of their capacity to span enormous areas. Castellated beams are used in many kinds of roof structures and floors nowadays **Figure (2)** .

There are several ways that castellated beams can fail. A few of the failure modes that are commonly studied are shear

* Corresponding author. Tel.: +201006351251
E-mail address: nehal82ayash@m-eng.helwan.edu.eg

failure, flexural failure, Vierendeel mechanism, local buckling, web post buckling or yielding, and rupture of welded joint [1] , see **Figure (3)**.

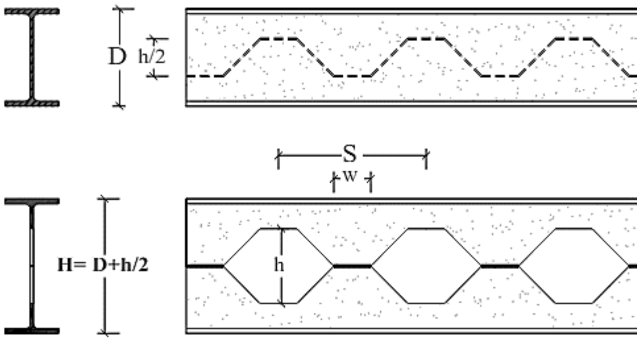
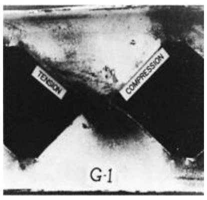


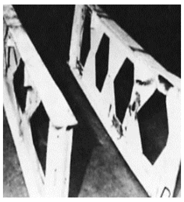
Figure 1 Castellated beams fabrication

Figure 2 Castellated beams application

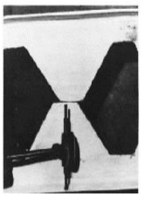
(a) Vierendeel mechanism[2]



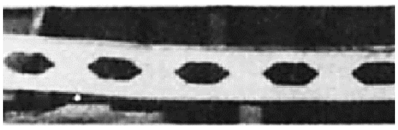
(b) compressive shear half-wave closes to a support [1]



(c) flexural buckling below a concentrated load [1]



e) Rupture of a welded joint



(d) flexural failure [1]

Figure 3 Different modes of failure for castellated beams

The recent previous studies were summarized as F. M. F. Shaker and Mahmoud Shahat, 2015 [3] reviewed the accuracy of applying Darwin rules for non-compact or slender sections of steel beams that have web openings. ANSYS has been used to build analytical study. The findings demonstrate that, in certain situations involving perforated beams with non-compact and narrow webs where the perforations are situated at both high moment and high shear zone, Darwin criteria may be applied. When the openings are situated in moment-shear combination zones, they cannot be utilized. It requires to be modified to be employed in these situations. The effect on the capacity of beams with non-compact sections due to web openings was investigated by F. M. F. Shaker and Mahmoud Shahat, 2015 [4], to identify the key sites of web holes. Consequently, assuming that the best method for web strengthening is determined by the size, shape, and the opening location in relation to the beam length. Because of their widespread and affordable applications, the study focuses on non-compact and thin web beams. The effectiveness of several stiffener types that are welded at the opening areas to enhance the beam's ultimate load carrying capacity was also examined in this study. The ANSYS software is used in analytical analysis, which considers both geometric and material nonlinearities. The optimal strengthening system, according to the collected results, is the longitudinal stiffener.

(K. D. Tsavdaridis , et al., 2015) [5] carried out an experimental and analytical examination to investigate the behavior of steel beams having openings that are closely spaced with innovative web opening configurations to study load strength of the web-post between two contiguous web openings and the failure mode. Also to better understand the practical "strut" action of web-post buckling, the influence of web opening spacing/web opening depth was examined. In addition, examination of the web-post stability exposed to vertical shear load and the impact of the web opening depth/web thickness were also investigated, the critical openings length is smaller and the Vierendeel capacity is higher when innovative elliptical web openings are considered. (K. D. Tsavdaridis , et al., 2015) [6]performed analytical structural topology optimization study, to find the optimized beam's performance against the traditional cellular beam. They find that the optimized beam performs better than the traditional perforated beam in terms of stress intensities, deformations, and load carrying capacities. They also recommend an optimized web opening arrangement, examine various methods for optimizing design topology for design routines. (Wang, et al., 2016) [7] examined the behaviors of the web-post shear buckling under vertical shear in a Castellated Steel Beam (CSB) with hexagonal web opening using ABAQUS to determine the factors that influencing the web post's vertical shear buckling strength, they conclude that shear buckling coefficient (k) grew linearly with the rise in the inclined angle of web opening edge (α) and opening height to web thickness ratio (h_0/t_w) and dropped nonlinearly with the rise in web-post width to web thickness ratio (e/t_w) and web height of Tee-section above the opening to the web thickness (h_f/t_w). The web post's vertical shear buckling strength is determined using the suggested shear buckling coefficient k showing a good agreement with the results of the numerical simulation, the suggested method relied on the web post's elastic buckling, it overstated the strength of shear buckling when the web post buckled in its elastic-plastic condition.

(W. Ji, et al., 2018) [8] investigated the buckling performance of beam webs, experimental tests were conducted under pure bending on castellated beams with various web compactness ratios and stiffener configurations. The results of the experimental work indicate that when there is only pure bending, most buckling appears on the web posts between the holes and the web zones above the holes. The behavior of the web as well as the whole behavior of the castellated beam can be achieved by lowering the web compactness ratio and adding stiffeners.

(Grilo, et al., 2018) [9] offered an investigation on the performance of web-post buckling in steel perforated beams. They studied the deformations of the web post and the vertical and lateral displacements of perforated beams using experiments and computational analysis with ABAQUS software. Additionally, they investigate an approach for determining the shear strength in perforated beams for web-post buckling. This approach was tested with a wide range of geometry and material properties, showing discrepancies up to 13% with the numerical models. The border effect in those beams was found to be expressive in short-span beams through a qualitative analysis.

(J. P. de Oliveiraa, et al., 2019) [10] provides a set of explicit equations that consider the relation between the web and flange to estimate the local buckling of castellated beams under pure bending. The eigenvalue studies are performed using the Finite Element Method to get data of the critical stresses and buckling scenarios for various cases of common flange-to-web width and thickness ratios. The prediction equations are derived using an energy approach, and the effects of web transverse bending and flange torsional stiffness on the "tee" behavior are examined.

(M.T. Nawar, et al., 2020) [11] conducted an extensive parametric study using “ABAQUS”, In order to prevent shear buckling of web posts, they offer suggested aspect ratios for web openings and spacing, Also provide minimum span limits, which indicate the point at which the ultimate load of castellated and cellular steel beams becomes more effective than the original beams , They set minimum span limits to show when castellated and cellular steel beams become more effective than parent beam , Additionally, offer a local P–M interaction technique that blends Vierendeel failures with web buckling.

(M.T.Nawar, et al., 2020) [12] conducted experimental and analytical analysis to investigate the energy absorption capabilities of castellated beams under blast load , they found that , CSBs are stronger beams than traditional ones due to it bends a lot before breaking (ductile failure) and having high energy absorption , Also stiffeners and bolted connections makes CSBs even better for handling blasts.

(S. Prabhakaran, et al., 2021) [13] They conducted experimental, analytical, and numerical to study on the behavior of stiffened and unstiffened simply supported cold-formed castellated steel beams to understand the behavior of the web under pure bending. The perforated web of the castellated beams represents an unusual advance in the history of short- and medium-length beams, three different types of stiffeners (parallel, perpendicular, and intercept stiffeners) at the Castellated beam's web. The various buckling scenarios and collapse of the suggested specimens have been examined, and an estimate of the beams' load capacity based on numerical analysis and experimental study.

(R. Shamass , et al., 2022) [14], under two-point load, the capacity of castellated beams with carbon fiber reinforced polymer (CFRP) and mild steel (MS) transverse stiffeners is computed using ABAQUS software and contrasted with a parent beam. The outcomes demonstrate that the transverse stiffeners of both materials increase the beams' capacity to support loads. They discovered that, on average, the load carrying capacity of beams with both types of stiffeners is 10.65% higher than that of the parent beam, with an 8% difference in load carrying capability between those with CFRP and MS stiffeners. Additionally, there was a 12.04% and 16% difference in the deflections of the parent beam and the beam with MS stiffeners, respectively. Additionally, because of their lighter weight, easier of use, and higher load carrying ability, CFRP stiffeners are the better option than MS stiffeners. (F. P. V. Ferreira, et al., 2023) [15] , The objective of that work is to apply the three high-strength steel grades (S460, S690, and S960) under research to the web-post buckling resistance equation, which was created using the truss model in accordance with EUROCODE 3. To adapt high-strength steels to the previously proposed equation, a new element was added. The regression, mean, standard deviation, variance, and comparison of the analytical and numerical models led to the determination of the statistical parameters, which were found to be 0.69%, 0.985%, 8.29%, and 0.98%, respectively.

The behavior of steel beam columns with apertures was examined under experimental and numerical investigations by Mona M. Fawzy et al. in 2024 [16]. The percentage of opening position from support to beam column length, web slenderness, opening shape, and the ratio of opening/specimen height are the characteristics that are being researched. Twelve specimens are used in experimental tests to record the failure load, load deflection curve, and stress strain curve while examining the effects of these parameters. Both local buckling and flexural buckling failure are noted. To broaden the parametric study, interaction curves generated from finite element model analysis are also utilized. Relocating the opening can reduce failure load by up to 60% and 7%, respectively, for both normal and moment ratios. The moment ratio can decrease by up to 74% and the axial ratio by up to 29% when the opening dimension is increased. Because of the unequal and concentrated loads surrounding the entrance, specimens with rectangular openings exhibit the weakest beam column behavior. The primary findings of this study show that the optimal opening location is between 40% and 50% from the support of the beam column. Moreover, in specimens with thin webs, circular apertures are preferable than rectangular ones due to the 85% increase in moment ratios that coincides with a 9% increase in normal ratios.

(Jia, et al., 2024) [17] conducted an experimental and analytical examination using "Abaqus" to examine how thin-walled castellated beams with deep tee sections buckle under bending stress. They found that adding a concrete slab or stiffener to the beam can prevent the web from buckling. They also developed a method to predict the peak load and buckling load of these beams.

(Carvalho, et al., 2024) [18] conducted a numerical model using "Abaqus" to examine how these beams behave under different loads and with different steel types. They used the "Artificial Neural Network" to investigate the validity of the current design rules; they concluded that the current design rules inaccurate and don't handle new high-strength steel well. So, they built a special computer program to help design these beams better.

(Oliveira, et al., 2024) [19] investigated analytically using "ABAQUS" and experimentally the effect of imperfections in steel beams with cavities (alveolar I-sections) on the stability of composite beams under bending. They found that considering the imperfections like residual stresses in the steel is crucial for accurate to make the predicted failure mode aligns better with experimental results.

2. Research Significant

The effectiveness of various sided stiffener types for perforated beams on slender and non-compact beams is investigated in [3] and [4] in order to increase the ultimate load carrying capacity of the beam; however, the effect on the castellated beam is not considered. In contrast, [5] focuses on the use of transverse stiffeners to reinforce castellated beams, specifically to strengthen web posts against local buckling or to strengthen under concentrated loads. Furthermore, they examine the mechanisms of failure (web-post shear buckling under vertical shear, shear performance, web-post buckling, elastic local buckling, Vierendeel, and flexural mechanisms in a Castellated Steel Beam (CSB)) in [7-8-9-10-11] and [12] respectively. The impact of a vertical stiffener on a cold-formed Castellated beam with a diamond aperture is examined in [13]. The impact of the carbon fiber vertical stiffener on the castellated beam's ultimate load is examined in [14], while the effects of steel grade on the web post buckling and slab on the local buckling of the tee web for castellated beams are examined in [15–17]. The web opening position, slenderness, shape, and ratio of opening to specimen height for beam columns are studied in [16].

The primary objective of the study is to determine the castellated beams' capacity as well as evaluate the effectiveness of various stiffeners configurations surrounding holes to enhancement of the beam load capacity. The behavior of castellated sections with slender, non-compact, and compact cases is covered in the article. The effects of four different types of stiffeners (horizontal, vertical, sleeve, and boundary) on the deformations, failure mechanism, and the castellated beams' load capacity are studied. This is accomplished by doing twenty-four nonlinear finite element studies of castellated beams, both with and without stiffeners, at different compactness ratios. This paper just examines the castellated beams with hexagonal holes that are simply supported and under two concentrated loads.

3. Numerical Study

Due to the high expense of conducting experiments, researchers have been using computers for this analysis in recent decades. To expand the scope of this investigation to include the behavior of castellated beams under different parameter values, three-dimensional finite element models were simulated using the ANSYS V23.1 [21] program. The experimental data discussed in the literature was used to cross-check and validate the finite element models' results. The behavior of castellated beams in the parametric investigation is represented by the model capabilities in this verification.

3.1. Verification Study

To check the accuracy of the models by authors, the three simply supported castellated beams tested experimentally by (Grilo, et al., 2018) [9] are considered in this comparison. W310*21.0 and W310*28.3 hot-rolled parent steel pieces were used to construct the models. **Table 1** and **Figure 4** present the average specimen measurements. As can be seen in **Figure 5**, a piece of equipment that restricted transverse movement when applying load to the top flange prevented the tested beams from lateral torsional buckling. To prevent stress concentrations from load application, full depth stiffeners with a thickness of 12 mm have been added to the edge and center stiffeners.

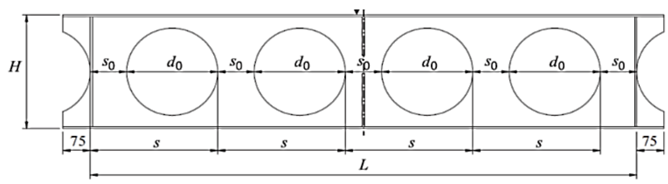


Figure 4: opening arrangement by (Grilo, et al., 2018) [9]

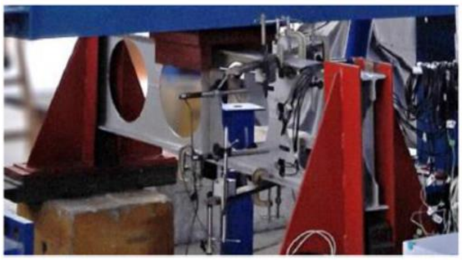


Figure 5: Test assembly for Considered specimens by (Grilo, et al., 2018) [9]

Table 1 Dimensions & Material Properties of Specimens Tested Experimentally by (Grilo, et al., 2018) [9]

Specimen	t_w	t_f	b_f	S_0	H	L	d_0	δ_w
	mm							
A5	4.8	6	102	325.1	409	1370	248.8	8
B5	5.9	9	99	318.4	412	1346	243.8	7.2
B6	6	9.2	98	343	409	1459	245	4.5

Where: (t_w) and (t_f) are web and flange thickness, (b_f) is flange width, (So) is solid part width, (H) is section depth, (L) is beam length, (d_o) is opening width, (δ_w) is an initial web post imperfection, Yielding stress (f_y) = 416 Mpa and Ultimate stress (f_u) = 480 Mpa.

The eight nodes that make up the SHELL281 element have six degrees of freedom apiece. The degrees of freedom involve rotations around the x, y, and z axes in addition to translations along them. Thin to moderately thick shell formations are better analyzed with this type of shell element. Without stain hardening, the material is modelled as a bilinear curve. The modulus of elasticity (E), which is equivalent to 200 GPA, varies depending on the specimen.

All the FE models are considered as simply supported beams in accordance with the experimental test setup. Restrain Rx prevents translation in x-direction at Edge surface (B), Restrain Rx &Rz prevent translation in (X & Z) direction at vertex D, Restrain Ry prevent translation in y-direction at Edge (A); see **Figure 6**. An analysis of linear elastic buckling was performed. in the castellated beam models. Also, the corresponding buckling modes and the critical buckling load were determined. The first global or local geometric imperfections were shaped by the global or local modes, respectively, which were assigned in the nonlinear analysis numerical models. The imperfection amplitudes are scaled by (δ_w/25) according to parametric analysis done by (Grilo, et al., 2018) [7] get the outcomes for each model, as displayed in **Table 1**, the first mode for eigen analysis for all specimens represents the buckling of web post between openings as shown in **Figure 7**.

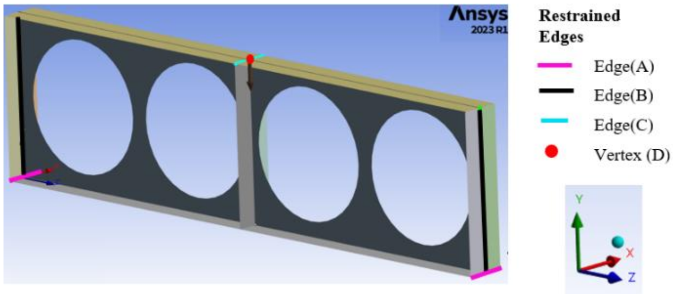


Figure 6: Specimen Restrains

Inside =(δ_w/25) deviation
Outside =(δ_w/25) deviation
Tolerance =0.01mm

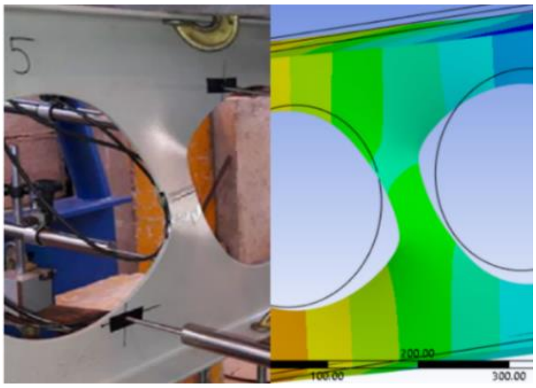
Figure 7: Eigen Buckling shape for First mode.

The mode of failure comparison between the experimental tests [9] and that obtained from FEM is presented in **Figure 8**. As shown, a similar failure mode can be captured using FE models and all specimens failed because of web-post-buckling (W.P.B) mode at the end of load /displacement curve.

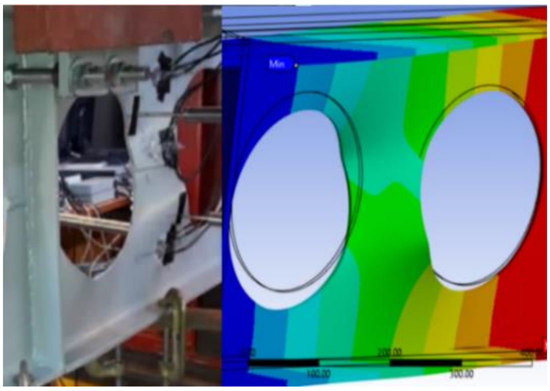
The load vs central displacement curves are plotted of a loss of stability mechanism using ANSYS for castellated beam specimens that are presented in **Figure 9**. **Table 2** will provide an illustration of the contrast between experimental results by Grilo, et al. [9] and FE analysis by authors. It is shown that the highest difference of mid-span deformation is around 12%, and the maximum variation in load capacity is approximately 7%. The experimental specimens and the FEM failure modes exhibit significant similarities. As a result, the numerical model can be applied to additional parametric research.

Table 2 Ultimate load and central deflection obtained experimentally by Grilo, et al. [9] and FEM by authors.

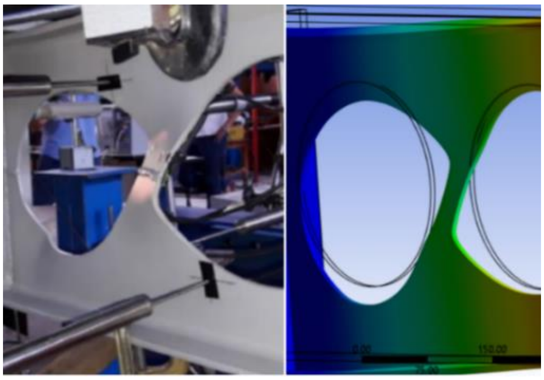
Specimen	Failure mode	Ultimate load (KN)		$\frac{FEM}{Exp}$ %	Central deflection(mm)		$\frac{FEM}{Exp}$ %
		Exp [9]	F.E.M		Exp [9]	F.E.M	
A5	WPB	184	198.2	7%	5	4.4	12%
B5	WPB	265.6	276.9	4%	3	2.9	3.5 %
B6	WPB	292.5	299.9	2%	4	3.7	7.5 %



A5-beam



B6-beam



B5-beam

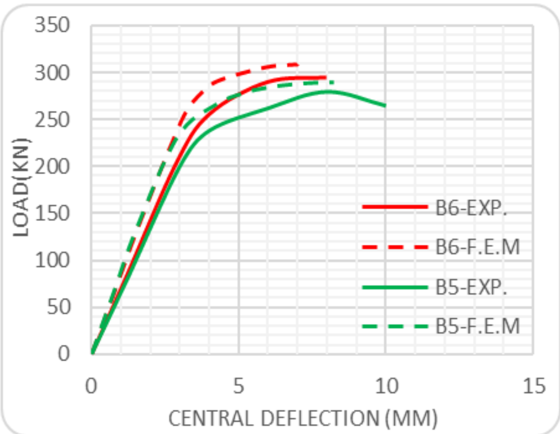


Figure 8: The failure modes for beam A5, B5 and B6 from FEM by authors and experimental tests by Grilo, et al. [9].

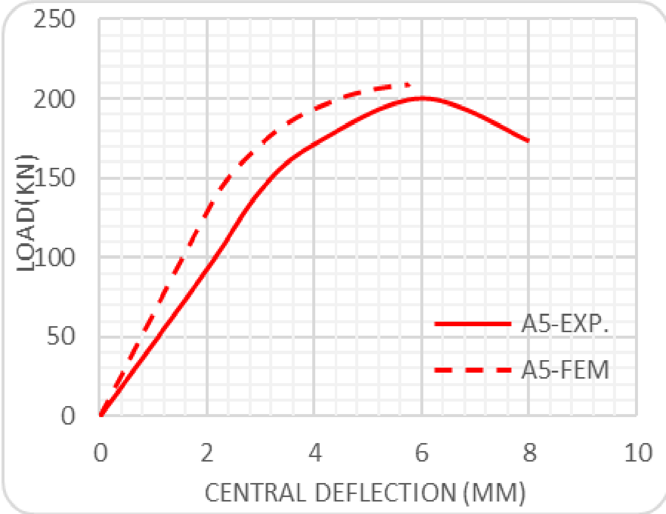


Figure 9: Load -Deflection Curve for Beam A5, B5 and B6; FEM by authors and experimentally by Grilo, et al. [9].

3.2. Parametric Study

With the aid of non-linear finite element models, a parametric analysis is conducted. As seen in **Figure 10**, the parent beams have been chopped and rewelded into beams with hexagonal apertures that are castellated. Each beam is given a unique name (Beam compactness – Stiffener types) in order to cover all the aspects that are being investigated. The section compactness (slender, non-compact, compact with/without a slender tee web above the opening) is indicated by the first parameter, "Beam compactness". **Tables 3 and 4** define the compactness checks (referred to as T-Sections above the opening and I-Sections at the solid part) based on AISC Specifications [22] and [23].

The second parameter, "Stiffener types," refers to the sleeve, boundary, vertical, and horizontal stiffeners as seen in **Figure 11** and **Table 5**. Twenty-four finite element models of castellated beams with various parameters were modelled and studied, as shown in **Table 6.**

“**C1**” refers to slender castellated beam, “**C2**” refers to non-compact castellated beam, and “**C3**” and “**C4**” refer to compact castellated beams with/without slender tee web above the opening, respectively. “**A**” refers to beams with castellated cross section. “**S**, **B**, **V** and **H**” are referred to stiffeners with sleeve, boundary, vertical, and horizontal patterns, respectively.

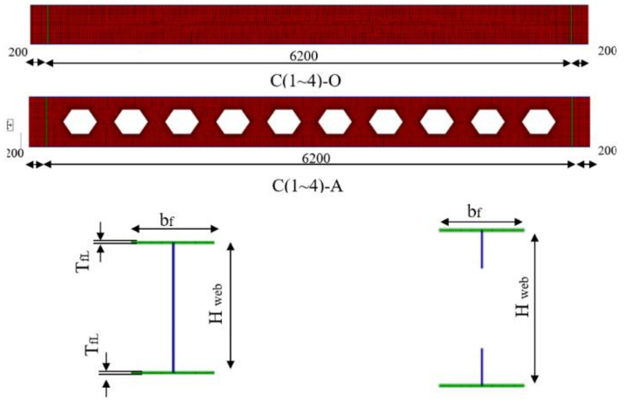


Figure 10 Specimen dimensions

Table 3 Specimen (dimension /compactness checks above the opening as T-Section referring to AISC [22,23]

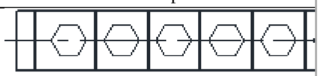
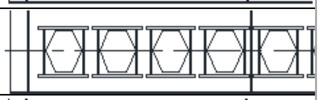
ID	Model	Section geometry				Compactness above opening as T-section						
		H_w	t_w	B_f	T_f	Flange	Web	Due to axial Class		Due to flexural Class		section class
						λf	λw	flange	web	flange	web	
C1	PB	450	4	200	8	---	----	----	-----	----	----	----
	CB	600	4	200	8	12	40	NS	S	NC	S	S
C2	PB	450	5	200	8	---	----	----	-----	----	----	----
	CB	600	5	200	8	12	32	NS	S	NC	NC	NC
C3	PB	450	8	175	9	----	----	----	----	----	----	----
	CB	600	8	175	9	9	20	NS	S	C	C	C
C4	PB	450	10	175	9	----	----	----	----	----	----	----
	CB	600	10	175	9	9	16	NS	NS	C	C	C

Table 4 Specimen (dimension /compactness checks above the opening as I-Section referring to AISC [22,23]

ID	Model	Section Geometry				Compactness Above Solid part				
		Hw	t_w	Bf	Tf	Flange	Web	Due To Flexural Class		Section Class
						Λf	Λw	Flange	Web	
C1	PB	450	4	200	8	12	108.5	NC	NC	NC
	CB	600	4	200	8	12	146	NC	S	S
C2	PB	450	5	200	8	11.8	86	NC	C	NC
	CB	600	5	200	8	11.8	116	NC	NC	
C3	PB	450	8	175	9	8.83	54	C	C	C
	CB	600	8	175	9	8.83	72.75	C	C	
C4	PB	450	10	175	9	8.6	43.2	C	C	C
	CB	600	10	175	9	8.6	58	C	C	

Where:
PB: Parent Beam
CB: Castellated Beam
NS: Non-Slender
S: Slender
NC: Non-Compact
C: Compact

Table 5 Full stiffener specimen

Stiffener Name	Specimen Name	Shape
Vertical stiffener	C (1~4)-A-V	
Horizontal stiffener	C (1~4)-A-H	
Boundary stiffener	C (1~4)-A-B	
Sleeve stiffener	C (1~4)-A-S	

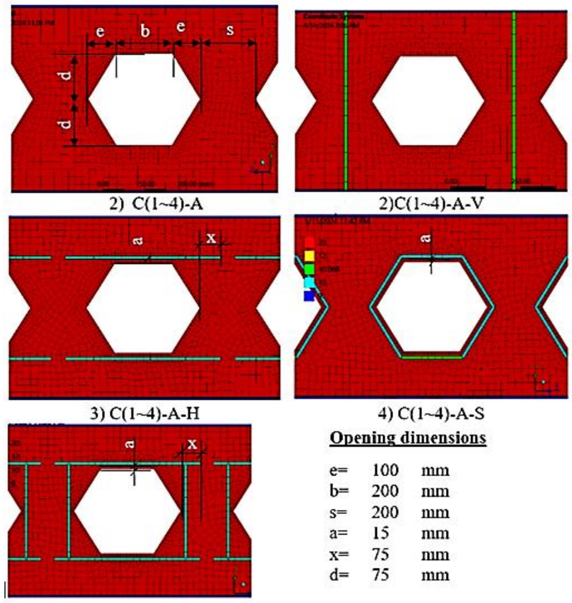


Figure 11 Beam Stiffeners Configurations

The material model is a bi-linear isotropic hardening curve with Elastic modulus (E) equal to 210 GPA, Tangential modulus equal to 0.5% of its elastic Modulus, with yielding stress (Fy) equals 355 Mpa and ultimate stress (Fu) equals 510 Mpa.

Restrain (UX) prevents translation in x-direction at vertex point (E, H, G, D), Restrain (Ux,y) prevents translation in (x,y) direction at edge (B), Restrain (Ux,y,z) prevent translation in (x,y,z), -direction at Edge (A) as shown in **Figure12**. Mesh size is 25mm according to previous studies where the mesh is finer close to the opening and denser farther away as shown in **Figure13.**

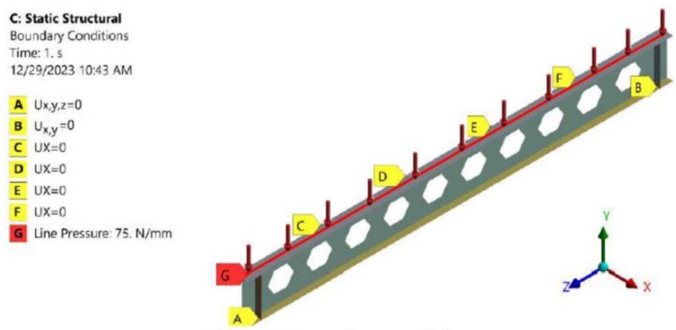


Figure 12 Boundary conditions

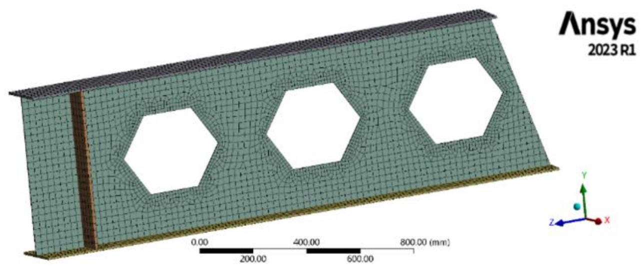


Figure 13 Meshing for Finite Element

3.2.1. Castellation effect:

Figure 14 represents the contrast of ultimate load vs central deflection of castellated beams and the corresponding parent beams.

The castellation decreased the ultimate load of the slender beams C1 by 35.6%. This was because the web depth increased from 450 mm to 600 mm, which caused the web to become slenderer. In addition, the mid-span deflection is lowered by 54.3% and this is due to the castellated section's moment of inertia is higher than that of the parent section.

For non-compact C2 castellated beams, a similar trend is shown, albeit with lower reduction ratios. Because the web depth increased from 450 mm to 600 mm, the castellation changed the compactness of the castellated web from compact to non-compact, reducing the ultimate load of the beams C2 in these beams by 1.5% as compared with similar parent sections. There is a 29.1% decrease in the mid-span deflection.

Conversely, in the case of beams with compact sections (C3 and C4), the castellation decreases the deflection by about 29.6-47.5% with average 39% while increasing the ultimate load by almost 30%. As a result, the compact section castellated beams were more effective.

Table 6 Specimen descriptions

No.	specimen Name	Compactness case	Beam Type	Stiffener Pattern	Stiffener type
1	C1	Non- compact	Parent	No	No
2	C2	Non- compact			
3	C3	Compact			
4	C4	Fully compact			
5	C1-A	Slender	Castellated (A)		
6	C2-A	Non- compact			
7	C3-A	Compact			
8	C4-A	Fully compact			
9	C1-A-V	Slender		Fully	Vertical
10	C1-A-H				Horizontal
11	C1-A-B				Boundary
12	C1-A-S				Sleeve
13	C2-A-V	Non- compact			Vertical
14	C2-A-H				Horizontal
15	C2-A-B				Boundary
16	C2-A-S				Sleeve
17	C3-A-V	Compact			Vertical
18	C3-A-H				Horizontal
19	C3-A-B				Boundary
20	C3-A-S				Sleeve
21	C4-A-V	Fully compact			Vertical
22	C4-A-H				Horizontal
23	C4-A-B				Boundary
24	C4-A-S				Sleeve

Table 7 Ultimate load and the central deformation of castellated beams and parent beams.

Specimens	Ultimate load $[P_U]$ (N/mm)	$[P_U]$ (Castellated)/ $[P_U]$ (Parent)	Central deformation $[\Delta]$ (mm)	$[\Delta]$ (Castellated)/ $[\Delta]$ (Parent)
C1	129	64.34%	35	45.7%
C1-A	83		16	
C2	130	98.5%	31	70.9%
C2-A	128		22	
C3	160	128%	44	70.4%
C3-A	205		31	
C4	174	132%	59	52.5%
C4-A	230		31	

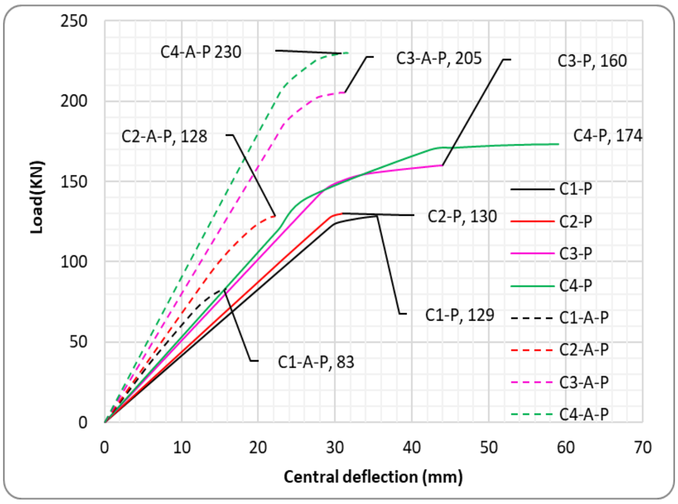


Figure 14 Comparison of ultimate load of castellated beam with Central deflection verses Parent beam

3.2.2. Effect of full-length stiffener patterns

In **Table 8**, ultimate load of castellated beams with varying compactness cases and stiffener patterns were enumerated and compared with the corresponding cases of parent beams and unstiffened beams. The impact of full-length stiffeners with different patterns (horizontal, vertical, sleeve, and boundary) on the load-central deformation relations is depicted in **Figures 15, 16, 17, and 18** for the non-compact case C2, the compact cases C3 and C4, and the slender case C1.

The comparison of the castellated beam's maximum load against its weight, with and without different stiffener patterns, is displayed in **Table 9** and **Figure 19**.

In general, stiffening the slender castellated beams increases the load carrying capacity by 7% when using a horizontal stiffener pattern, 50% when using a vertical stiffener pattern, and 43% when utilizing sleeve and boundary stiffener patterns. This is more effective than stiffening the non-compact castellated beams.

Stiffening the compact (With/without slender web) castellated beams using any stiffeners patterns (horizontal, vertical, sleeve, or boundary) has smallest impact on enhanced the capacity of these beams, the enhancement is reached to 10% as maximum.

Vertical stiffener increases the ultimate load capacity of the slender and noncompact castellated beams compared to that are without stiffener by (95%, 31%) respectively, while it shows no impact on the compact castellated beam, The Vertical stiffener for castellated beam (slender and noncompact) rises the ultimate load capacity of the solid specimen by (26%, 29%), respectively. It increases the weight of (castellated beam without stiffener/ solid) by 18%, 16%.

Horizontal stiffener increasing the ultimate load on the (slender/noncompact) castellated beam by (37%, 28%), while the horizontal stiffener for castellated beam compact web, increases the ultimate load capacity by (10%, 4%) respectively than castellated beam without stiffeners. As shown in Figure 19, horizontal stiffener increases the weight of (castellated beam without stiffener/parent beam) by 24%.

Boundary and sleeve stiffener shows that they have a great impact on the maximum load capacity for slender and noncompact castellated beams. While these both patterns show less impact on the compact (With/without slender web) castellated beam that are ranged between 2-9% amplifications. For (slender/noncompact) castellated beam, negligible differences on the amplification effect on the maximum load between the Boundary stiffener and the sleeve stiffener, this difference is about 5%, while the average weight verses ultimate load study shows that the sleeve stiffener is less in weight by 12 % than the boundary stiffener. So, sleeve stiffener pattern is more economic than boundary stiffener pattern for slender/noncompact castellated beams. The sleeve stiffener shows less impact on the compact (With/without slender web) castellated beam by 3%, 5% than boundary stiffener respectively.

Boundary stiffener has same impact of horizontal stiffener on the ultimate load capacity of the compact (With/ Without slender web) but with weight increases by 12 ,11 %. So horizontal stiffener is more economic.

The Sleeve stiffener increases the ultimate load capacity of the castellated beam compared to those without stiffener for (slender/noncompact) by (105%, 43%) respectively, while it shows less impact on the compact castellated beam by (5%, 2%). The Sleeve stiffener for castellated beam (slender/noncompact) beam improves the ultimate load capacity of the solid specimen by (33%, 41%) respectively. While it increases the weight of (castellated beam without stiffener/ solid) by 33, 43% respectively as shown in **Figure 20**.

Table 8 Ultimate load of castellated beams with different compactness cases having different Full-length stiffeners patterns.

	Parent beams	Castellated beams								
		Unstiffened	Ultimate load (kN) and $\frac{Stiffened}{Un-stiffened}$ %							
			Horizontal		Vertical		Sleeve		Boundary	
				%		%		%		%
C1	129	83	114	**137%**	162	**195%**	171	**205%**	175	**210%**
C2	130	128	165	**128%**	168	**130%**	183	**143%**	188	**147%**
C3	160	205	227	**110%**	208	**101%**	216	**105%**	223	**109%**
C4	174	230	240	**104%**	230	**100%**	234	**102%**	245	**107%**

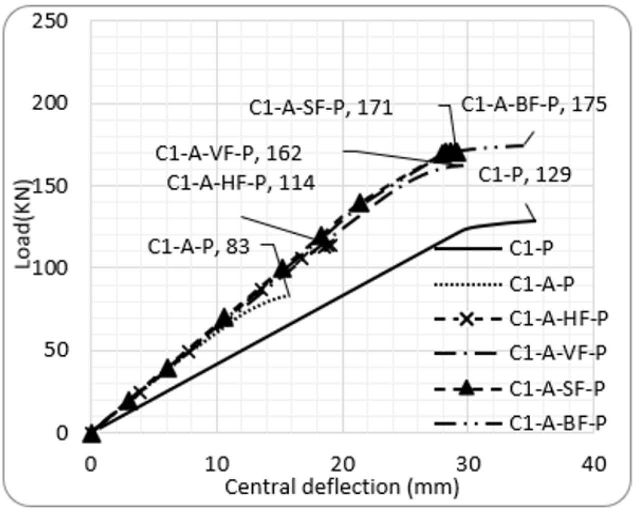


Figure 15 load- deflection curves of slender castellated beams (C1) without / with stiffener patterns.

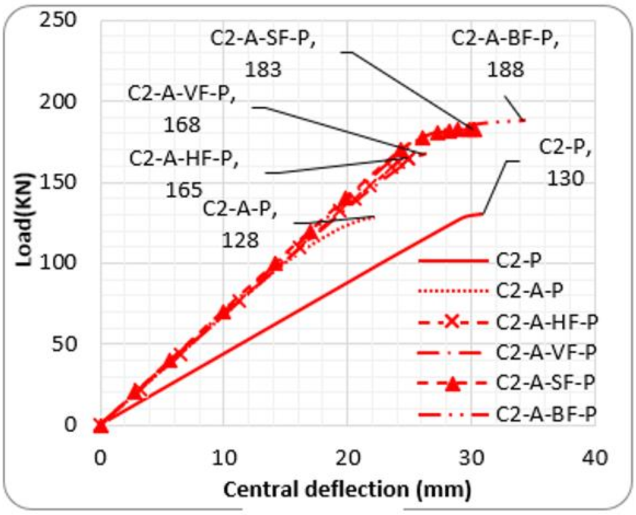


Figure 16 load- deflection curves of non-compact castellated beams (C2) without / with stiffener patterns.

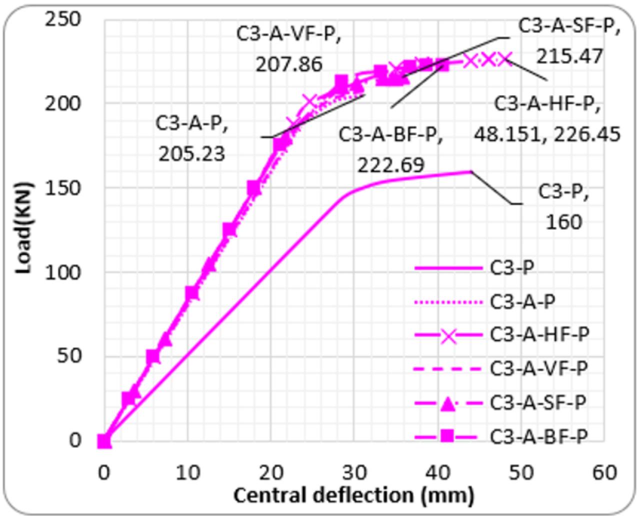


Figure 17 load- deflection curves of compact castellated beams (C3) without / with stiffener patterns.

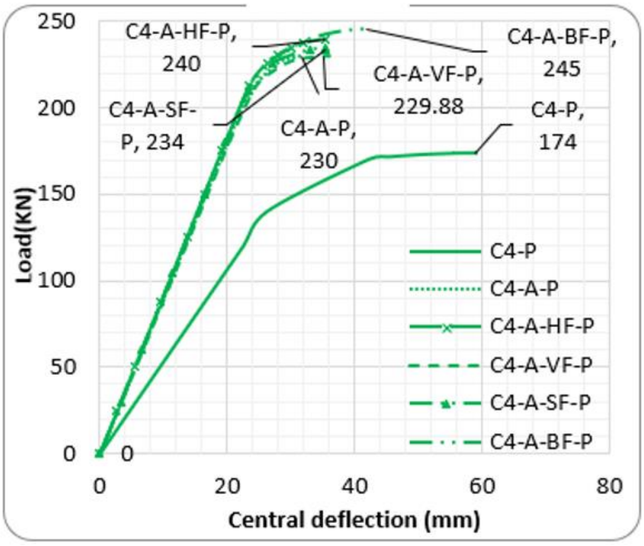
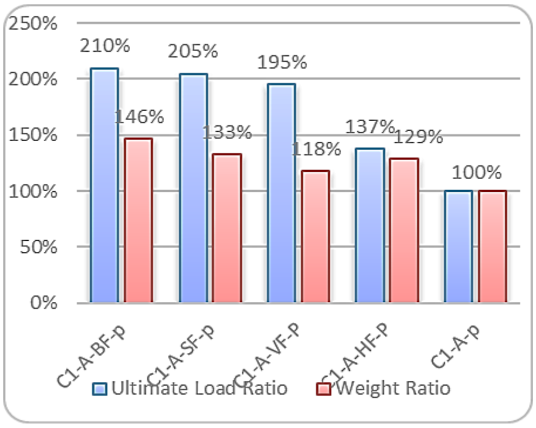


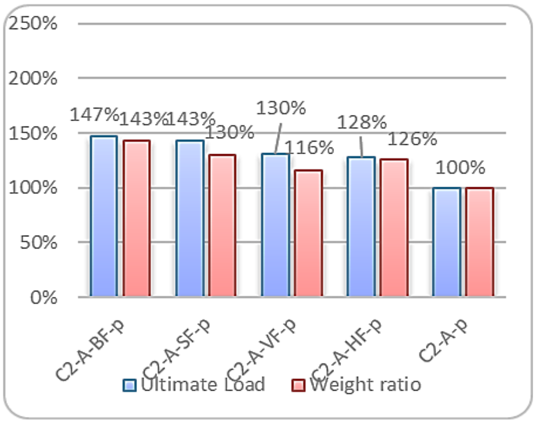
Figure 18 load- deflection curves of compact castellated beams (C4) without / with stiffener patterns.

Table 9 Weight of parent beams and castellated beams with different compactness cases, unstiffened and stiffened with different stiffeners patterns.

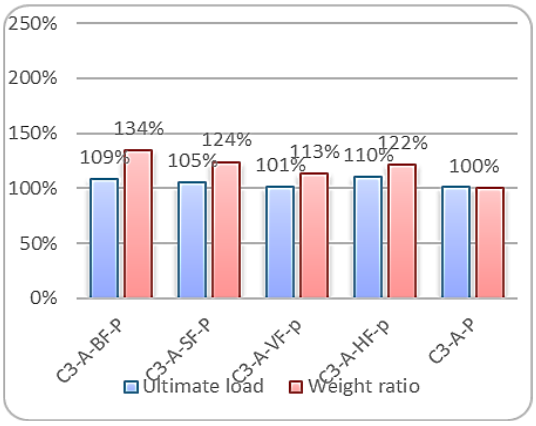
	Parent beams	Castellated beams								
		Unstiffened	Full-length Stiffened							
			Weight (kg) and $\frac{Stiffened}{Un-stiffened}$ %							
			Horizontal		Vertical		Sleeve		Boundary	
				%		%		%		%
C1	286	286	368	129%	337	118%	380	133%	417	146%
C2	310	310	390	126%	350	113%	403	130%	443	143%
C3	380	380	463	122%	429	116%	471	124%	509	134%
C4	429	429	510	119%	480	112%	519	121%	557	130%
Average			124%		115%		127%		139%	



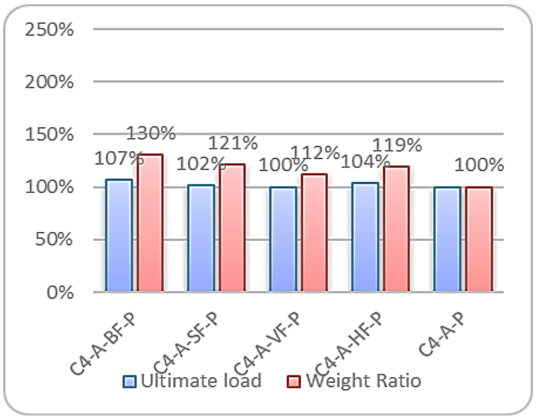
C1



C2



C3



C4

Figure 19 Comparison of ultimate load and wight of castellated beams unstiffened and stiffened with different stiffeners patterns.

3.2.3. Failure modes

The Von-Mises stress for specimens included slender (C1), non-compact (C2), and compact sections (C3 and C4) of castellated beams that were both unstiffened and stiffened with different patterns (horizontal, vertical, sleeve, and boundary) are presented in **Figures 20**.

For cases of slender specimens (C1) as well as noncompact specimens (C2), the failure mode of unstiffened specimen and stiffened specimen by horizontal stiffener is web post buckling (W.P.B.) near the supports. It can be explained that the tee sections over and beneath the opening transfer the load to web regions between openings causing stress concentration. This concertation causes large lateral displacement due to local buckling in web regions between openings causing the (W.P.B.).

In cases of stiffening the holes with boundary or sleeve stiffeners, the failure mode is changed to flexural failure. The flexural failure occurred at mid span due to yielding in the flange at the maximum capacity of the section. The boundary and sleeve stiffeners have a significant impact of forbidding the lateral deformations of the web regions between the openings which led to increase their shear capacities.

The failure of the unstiffened compact specimens (C3&C4) occurred due to Vierendeel action. The local bending moment of the tee regions over and beneath the opening is a result of spreading of the shear force through them, causing an excessive increase of tension and compression at the opening's corners. This effect triggers the corners to plasticize, causing failure. But in the stiffened specimens with different stiffener patterns, the specimens failed at mid span as flexural mode failure. The stiffeners have a significant effect, where there prohibited the lateral deformations in web regions around the opening which cause the failure in the middle third of the span due to the yielding in the flanges.

4. Conclusions

A FE theoretical analysis was performed with ANSYS Workbench concerning two concentrated loads for full-length stiffened castellated beams with hexagonal holes. There was a total of 24 computational models. The investigated factors were the (beam compactness and stiffener patterns). The studied stiffener patterns are vertical, horizontal, sleeve, and boundary configurations. The key findings are as follows:

1- The web-post-buckling (W.P.B) failure mechanism of castellated beams is well captured by the finite element models, and the highest differences between the analytical and experimental results are approximately 12% for deflections and 7% for load capacity.

2- The castellation of beams with compact sections proved to be more effective due to reducing beam deflection by %39 and increasing load capacity by 30%.

3- Conversely, the castellation of non-compact and slender beams is not efficient due to lowering the load capacity, this is because of the change in compactness case brought about by deepening the beam and the sections become weaker. On the other hand, the castellation of non-compact and slender beams is lowering the deflection due to increasing the moment of inertia of section.

4- It is more effective to stiffen the slender castellated beams than the non-compact castellated beams.

5- Using any pattern of stiffeners—horizontal, vertical, sleeve, or boundary—to stiffen compact castellated beams with or without a thin web has little effect on increasing their capacity; the greatest increase is 10%.

6- Stress concentration resulting from the tee portions above and below the opening transmit the load to web areas between openings is the cause of the web post buckling (W.P.B.) failure mechanism for unstiffened castellated beams. Due to local buckling in the web regions between apertures, this concertation results in significant lateral displacement.

7- When stiffened by boundary and sleeve stiffeners, the failure mode shifted from web post buckling (W.P.B.) to flexural failure for cases of slender specimens and non-compact specimens. However, there is no way to alter the mode failure with the horizontal stiffeners.

8- The local bending moment of the tee regions over and beneath the opening is produced by the spreading of the shear force through them, causing an excessive increase in tension and compression at the corners of the opening. This is the reason for the Vierendeel action for the cases of unstiffened compact specimens (With and without slender web tee above the opening). Failure results from this reaction, which causes the corners to plasticize.

5. Future works

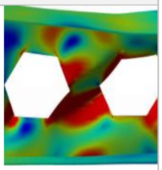
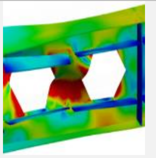
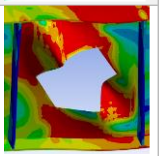
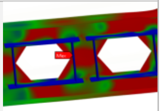
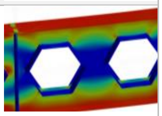
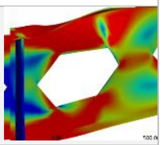
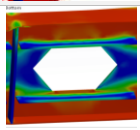
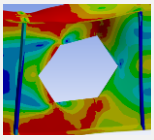
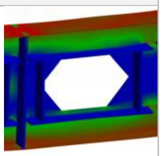
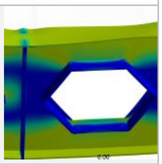
More studies using different cross section, Beams span length, and different opening dimensions and spacing can be studied.

Studies can be conducted on various opening shapes found in castellated beams, such as circular, octagonal, and elliptical openings.

One can study various load patterns, including single or double concentrated loading.

It is possible to study the effects of using fiber reinforced polymer (FRP) stiffeners rather than steel ones, which aim to reduce the structure's weight and raise the stiffness of the web portion surrounding openings.

Figure 20 Failure Criteria for castellated beam without / with stiffener patterns by the end of load /displacement curve

Specimen	**Stiffener**	Failure Mode	Location	Von mises Stress
C1, C2	Unstiffened	W. P. B	Edge Rare from support	
	Horizontal stiffened	W. P. B		
	Vertical stiffened	Shear Failure of Web	Edge Rare from support	
	Boundary stiffened	Flexural	Mid span	
	Sleeve stiffened	Flexural	Mid span	
C3, C4	Unstiffened	Vierendeel bending of Tee	Rare from support	
	Horizontal stiffened	Flexural	Mid span	
	Vertical stiffened	Vierendeel bending of Tee	Rare from support	
	Boundary stiffened	Flexural	Mid span	
	Sleeve stiffened	Flexural	Mid span	

References

[1] Kerdal D. and Nethercott D. A. “Failure Modes for Castellated Beams”, J. Construct. Steel Research 4 (1984) 295-315

[2] Hayder A. “Experimental study of effect of hexagonal holes dimensions on ultimate strength of castellated steel beam”, 2017. [Online]. Disponível em: https://www.researchgate.net/publication/317951982

[3] Fattouh M. F. S. and Mahmoud S., “Study of Darwin guidelines for non-compact and slender steel girders with web openings” IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) e-ISSN: 2278-1684, p-ISSN: 2320-334X, Volume 12, Issue 5 Ver. I (Sep. - Oct. 2015), PP 72-85

[4] Fattouh M. F. S. and Mahmoud S., “Strengthening of web opening in non-compact steel girders” IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) e-ISSN: 2278-1684, p-ISSN: 2320-334X, Volume 12, Issue 5 Ver. II (Sep. - Oct. 2015), PP 34-47

[5] Konstantinos D. T. and Grigorios G., “Assessment of cellular beams with transverse stiffeners and closely spaced web openings”, Thin-Walled Structures, vol. 94, p. 636–650, set. 2015, https://doi.org/10.1016/j.tws.2015.05.005

[6] Konstantinos D. T., James J. K., and Vassilli V. T. “Application of structural topology optimisation to perforated steel beams”, Comput Struct, vol. 158, p. 108–123, jul. 2015, https://doi.org/10.1016/j.compstruc.2015.05.004

[7] Peijun W Kangrui G., Mei L.,and Lulu Z. “Shear buckling strengths of web-posts in a castellated steel beam with hexagonal web openings”, J Constr Steel Res, vol. 121, p. 173–184, jun. 2016, https://doi.org/10.1016/j.jcsr.2016.02.012

[8] Wenting J., Lianguang J., Yuhan W. and Chen C. “Experimental Study of Local Buckling of Castellated Steel Beams under Pure Bending”, em IOP Conference Series: Materials Science and Engineering, Institute of Physics Publishing, ago. 2018. https://doi.org/10.1088/1757-899X/392/2/022013

[9] Lucas F. G., Ricardo H. F., Ana Lydia R. C. S., and Gustavo S. V. “Design procedure for the web-post buckling of steel cellular beams”, J Constr Steel Res, vol. 148, p. 525–541, set. 2018, https://doi.org/10.1016/j.jcsr.2018.06.020

[10] Julia P. O., Daniel C. T. C., and Elisa D. S. “Elastic flexural local buckling of Litzka castellated beams: Explicit equations and FE parametric study”, Eng Struct, vol. 186, p. 436–445, maio 2019, https://doi.org/10.1016/j.engstruct.2019.02.034

[11] Mahmoud T. N., Ibrahim T. A., and Osama E. “Numerical investigation on effective spans ranges of perforated steel beams,” Structures, vol. 25, pp. 398410, Jun.2020, https://doi.org/10.1016/j.istruc.2020.03.026

[12] Mahmoud T. N., Ibrahim T. A., Osama E., and Ayman E. “Full static resistance of castellated steel beams with hexagonal web openings for blast response predictions,” Eng Struct, vol. 245, Oct. 2021, https://doi.org/10.1016/j.engstruct.2021.112844

[13] Prabhakaran, S. and Maboob, S.A. Numerical Analysis and Experimental Investigation on Behavior of Cold-Formed Steel Castellated Beam with Diamond Castellation. Int J Steel Struct 21, 1082–1091 (2021). https://doi.org/10.1007/s13296-021-00494-x

[14] Rabee S., Felipe P. V. F., Vireen L., Luis F. P. S., and Konstantinos D. T. “Web-post buckling prediction resistance of steel beams with elliptically based web openings using Artificial Neural Networks (ANN)”, Thin-Walled Structures, vol. 180, nov. 2022, https://doi.org/10.1016/j.tws.2022.109959

[15] Felipe P. V. F., Rabee S., Luis F. P. S., Konstantinos D. T., and Vireen L. “Web-post buckling resistance calculation of perforated high-strength steel beams with elliptically-based web openings for EC3”, Structures, vol. 55, p. 245–262, set. 2023, https://doi.org/10.1016/j.istruc.2023.05.139

[16] Mona M. F., Fattouh M. F. S., Alia M. A. and Mohamed M. S. “Influence of opening location, shape, and size on the behavior of steel beam columns” Steel and Composite Structures, Vol. 50, No. 1 (2024) 1-13 https://doi.org/10.12989/scs.2024.50.1.001

[17] Lianguang J., Qiurong L., Wenting J,, Chen C., and Jiahui D., Kai G. “Influence of the local buckling of web on the bearing capacity of a castellated beam/composite beam under pure bending”, Structures, vol. 63, May 2024, https://doi.org/10.1016/j.istruc.2024.106358

[18] Adriano S. C., Alexandre R., Marcela M. Rocha A., Yasin O. Ö., and Carlos H. M. “Artificial neural network modeling of the stability behavior of stainless-steel I-beams with sinusoidal web openings, Engineering Structures Vol. 304 (2024) (1,20), 13 Feb.2024, https://doi.org/10.1016/j.engstruct.2024.117579

[19] Vinicius M. O., Lucas M. S. P., Alexandre R., João P. M., Luís A. P. S. S., Carlos H. M. “Comparative analysis of geometric imperfections

and residual stresses on the global stability behavior of cantilever composite alveolar beams "Structures Vol. 65 (2024) (1-26), 7 June 2024, https://doi.org/10.1016/j.istruc.2024.106634

[20] ANSYS R2023-R1, "Release 23 Documentation for ANSYS," in ANSYS, 23.1 ed.Canonsburg, PA, USA, 2023.

[21] AISC Design Guide 31; Castellated and Cellular Beam Design. American Institute of Steel Construction, 2016.

[22] ANSI/AISC 360-16; American Institute Of Steel Construction Standard Specification for Structural Steel Buildings.