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Ultimate Load Behaviour of Castellated Beams with Stiffened Octagonal Openings

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ABSTRACT

Octagonal castellated beam is fabricated by adding spacer plates between the web joints of the hexagonal castellated beam to further increase the beam depth. The resulted deep beam is advantageous to enhance the shear carrying capacity and moment resistance. However, large web openings are prone to Vierendeel mechanism in the deformation that lowers the overall beam performance due to formation of plastic hinges. The present paper is concerned with non-linear analysis to predict the ultimate load behaviour of octagonal castellated beams. Finite element models were developed by using a commercial programme LUSAS. The numerical models were first validated against the experimental results reported by other researchers. This study aims to propose the ideal configuration of web opening stiffeners and evaluate the effectiveness of the additional stiffening material for different beam span lengths. Provision of ring stiffeners is effective in short span beams in respect of resistance to Vierendeel failure. The stiffeners have increased the ultimate load to the extent of 73% in which the strength restoration is considerably near to the capacity of its parent universal beam. In long span beams, however, the stiffeners can only improve the performance up to 26.61% with larger additional steel material than that of shorter span. In all cases, the stiffener thickness is found to be the governing factor to restoring the loss of shear strength due to large web openings. The number of stiffeners contributes no appreciable variation of ultimate load particularly in long span beams where bending is prominent.

Keywords: Octagonal castellated beam; Stiffened web opening; Finite element analysis; Ultimate performance; Vierendeel deformation

INTRODUCTION

Conventional steel beams are often modified to castellated beams to exploit the greater section depth for better moment resistance and directly increase the load bearing capacity (Boyer 1964). Such beams are commonly used in modern long span constructions that require large interior open space with a smaller number of columns and foundations, hence economical and elegant (Nawar et al. 2020). The castellated beam is produced by cutting a universal beam into two parts with a cut profile as shown in Figure 1. One of the separate parts is shifted in the direction of the beam length and welded to another part to produce a new beam having web openings and greater section depth.

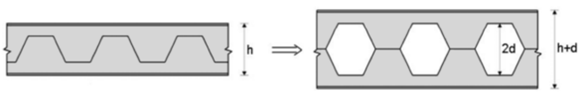


FIGURE 1. Cut profile of castellated beam (Gandomi et al. 2011)

The octagonal castellated beam is an extension from the hexagonal castellated beam to further increase the beam depth by adding steel plates between the beam peaks, thus producing a much deeper section. The process is shown in Figure 2. Such deep member allows it to bear higher loads without significant gain in weight. The web openings permit passage for mechanical, electrical, plumbing and other building services systems without re-routing. In addition, the series of openings provide the aesthetic value to buildings.

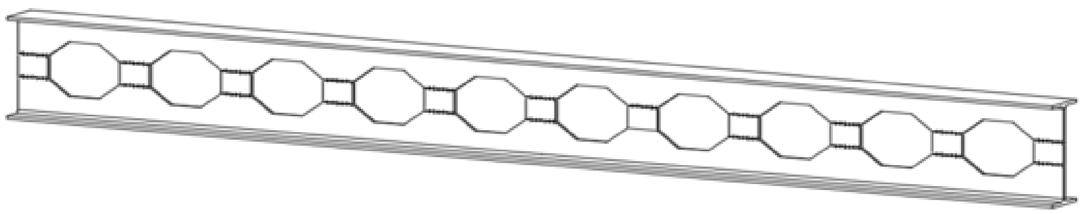


FIGURE 2. Octagonal castellated beam (Al-Thabhawee & Mohammed 2019)

In general, an increase in beam depth only means an enhanced load carrying capacity but the presence of considerably large-sized web openings makes castellated beams highly susceptible to local buckling and lateral torsional buckling (Ellobody 2011). Castellated beams with opening shape like Vierendeel trusses are also influenced by the Vierendeel mechanism. The shear force is transferred through the web opening and drives a local bending mechanism at the edge of the web opening causing stress concentration around the opening. Stress concentrations for different opening shapes are shown in Figure 3. Such failure mode does not occur in universal steel beams.

To fully exploit the benefits of octagonal castellated beams, failure modes caused by perforated slender web should be avoided. Studies have been conducted by past researchers in an effort to increase beam loading capacity. Stiffeners can be added to web openings or installed vertically between the openings to reduce shear stress concentration at the vicinity of the cut-outs as well as increasing buckling resistance. However, the extra weight resulting from the installation of stiffeners is not beneficial to the structure. The balance between the improvement of load-bearing capacity and the overall weight gain as a consequence of adding the reinforcement needs to be studied further so that an optimal design can be produced.

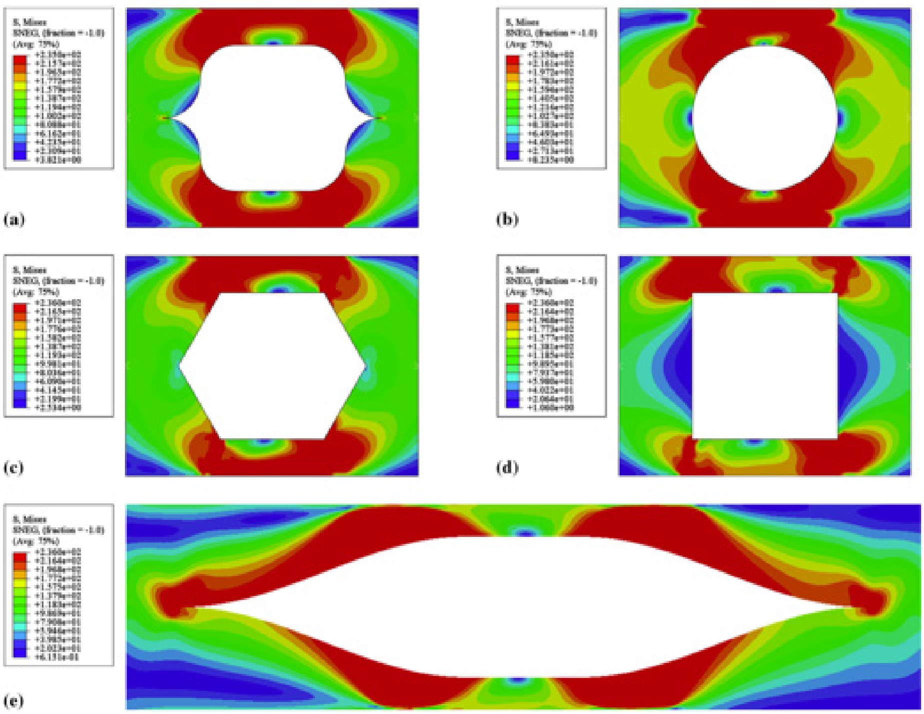


FIGURE 3. Stress concentration in various castellated beam (Wang et al. 2014)

Weaknesses as a result of Vierendeel failure, local buckling, web-post buckling, lateral torsional buckling and flexural buckling of hexagonal castellated beams have been examined by in prior and various suggestions to enhance the performance and buckling resistance have been reported. Amongst others are by installing the ring stiffeners around the edge of openings (Morkhade et al. 2020) and vertical stiffeners between the openings.

In the present study, effects of opening stiffeners on the ultimate load behaviour of octagonal castellated beams is investigated in order to recommend the optimal stiffeners configuration and design. The castellated beams are simply supported and subjected to a single concentrated load at the middle span. Non-linear finite element analysis was performed using LUSAS package. Different beam span lengths, dimensions of the opening stiffeners and their arrangements are accounted for in the analysis to highlight their influences on ultimate carrying capacity, load-displacement response, failure characteristic and stress distribution. Weight-capacity analysis was also carried out to evaluate the effectiveness of additional steel material allocated for the stiffeners to be used in real constructions.

FINITE ELEMENT ANALYSIS

VERIFICATION OF FINITE ELEMENT MODEL

It is imperative to validate the finite element model before using LUSAS for further analysis. To ascertain the accuracy of the non-linear analysis, validation of model has been made by means of comparison with the corresponding results obtained from the experiments on plate girders and octagonal castellated beams conducted by past researchers. Various principles, assumptions and modelling attempts have been accounted for in order to mimic the conditions of the test specimens so that deviation from the actual behaviour can be minimised.

In compliance with the intentions of this study, plate girders SPG1 and SPG2 from experimental work by Shanmugam and Baskar (2003) and octagonal castellated beam tested by Al-Thabhawee and Mohammed (2019) were selected for model verification. These specimens were simply supported and tested to failure under a central concentrated load. The geometrical details and mechanical properties of them can be found in the papers. A regular quadrilateral finite element mesh of size 50×50 mm was employed after performing a convergence study in order to determine the ideal element size that produces a relatively accurate solution within an appropriate computational cost. Consequently, all the three models have shown acceptable accuracy when compared with the corresponding test data in terms of ultimate load, load-deflection relationship and failure mode.

MODELLING DETAILS

Selection of suitable elements is necessary as they dictate the behaviour of the model. The geometries of web, flanges and stiffeners were meshed with three-dimensional thin shell elements (QSL8). Each of the elements consists of four corner nodes and four intermediate nodes. The element formulation takes account of membrane, flexural and transverse shear deformations which are suitable in the present application. A consistent formulation of the tangent stiffness makes this element particularly effective in geometrically non-linear treatment. The QSL8 element comprises six degrees of freedom viz., translations and rotations with respect to global axes at each node.

Beams and stiffeners were modelled as an isotropic elastic-perfectly plastic material in both tension and compression, giving a uniaxial stress-strain relationship. The modulus of elasticity E and yield stress f_y were set to be 200 GPa and 279 MPa, respectively. These parameters are needed to define the stress potential material model. The Poisson's ratio of steel material was conservatively taken as 0.3. The non-linear properties are based Von-Mises yield criterion which represents the ductile behaviour of steel material that exhibits little volumetric strain.

Proper boundary conditions were imposed to the numerical model to reflect the actual support conditions in the past experiments. As presented in Figure 4, pin and roller support were assigned at the nodes along a line across the width of bottom flange to simulate simply supported condition. At the pin support, the girder was restrained against the displacements in global x, y and z directions but free to move along z direction at roller support. Nevertheless, rotations about all directions were allowed for in both types of support conditions.

A vertical concentrated load was applied to the castellated beam incrementally. An automatic load increment with Crisfield's arc length control was chosen. Newton-Raphson solution strategy with a particular number of iterations was used to provide convergence at the end of each load increment within tolerance limits. Also, load step reduction with specified reduction factor and increase factor was allowed for. This procedure has a potential to step over a difficult point in the analysis so that the solution can proceed to lead to convergence. Termination of analysis was limited to the default criteria.

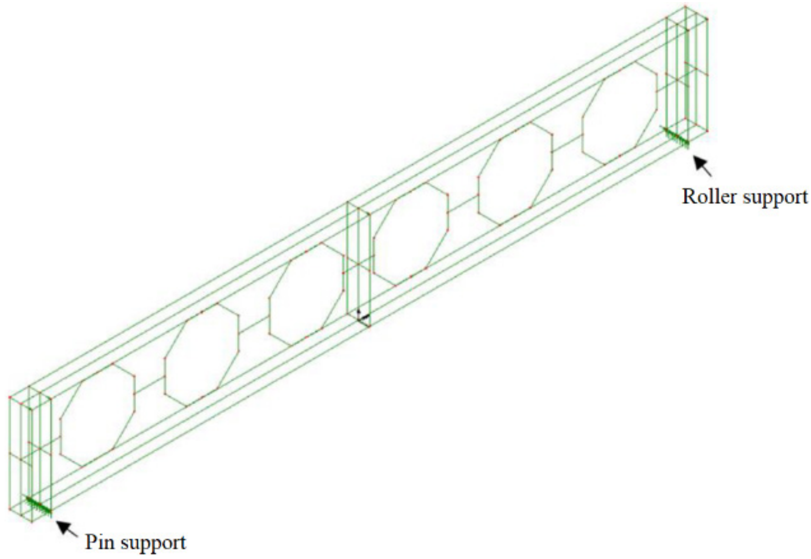


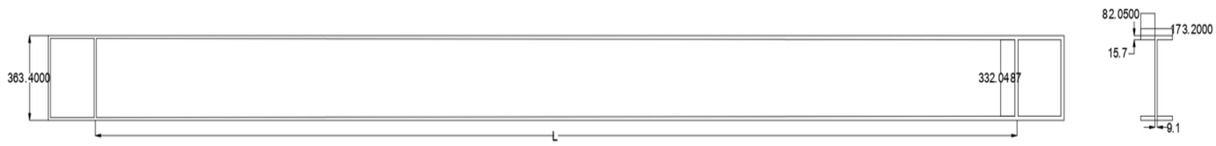
FIGURE 4. Assignment of boundary conditions

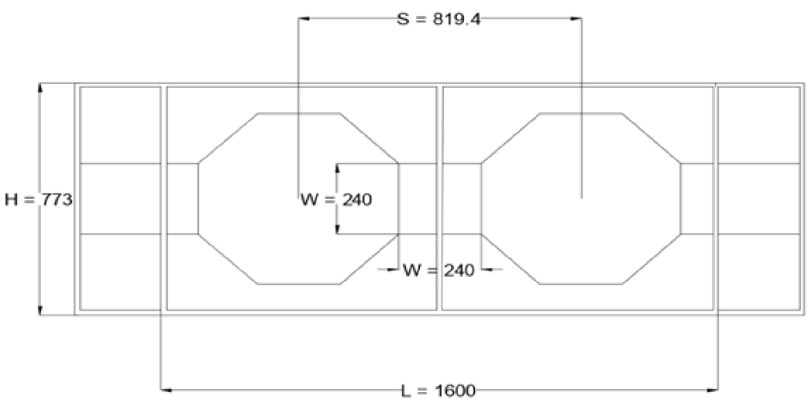
PARAMETRIC STUDY

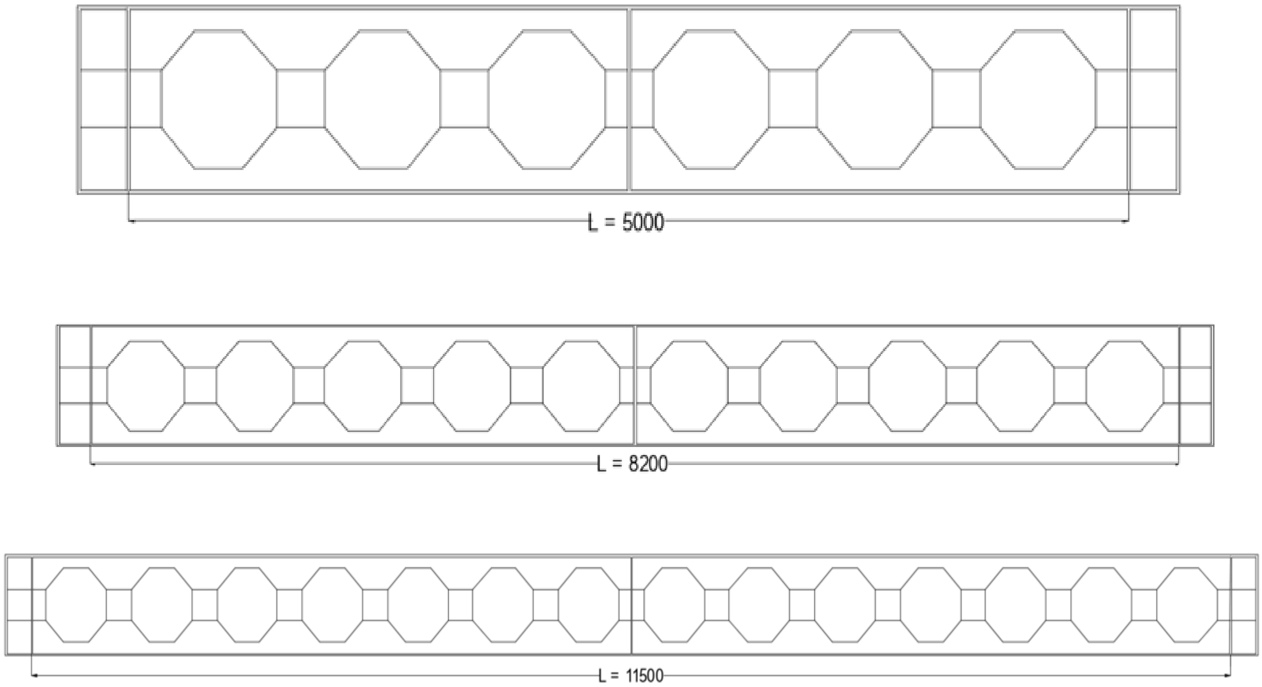
This study involves parametric modelling of 37 stiffened octagonal castellated beams with the aim of investigating the ultimate load behaviour and identifying the appropriate stiffener thickness, width and arrangement. The parent universal beams and the corresponding unstiffened octagonal castellated beams were also considered for control model. UB 356×171×67 was used as the parent member of the castellated beam.

The analysis was performed in three sets; varying the thickness, width and arrangement of the stiffeners. In each set of analysis, there are beams with four different slenderness with L/H = 2.07, 6.47, 10.61 and 14.88 in which, L is span length and H being the depth of beam. Table 1 lists the details of octagonal castellated beam models. Figures 5 and 6 illustrate the configurations of beams and opening stiffener, respectively.

Analysis 1 was aimed at identifying the effect of stiffener thickness. The thicknesses examined are $0.25t_f$, $0.5t_f$, $0.75t_f$ and $1t_f$. Analysis 2 dealt with different widths of opening stiffeners, viz. 0.25b, 0.5b, 0.75b and 1b whilst Analysis 3 was carried out to study the ideal stiffener arrangement in the beam openings. In Table 1, n indicates number of openings in the beam whilst notations 2h, 4h, 6h, 8h, 10h and 14h, however, refer to number of openings being stiffened along the beam. Other dimensions are shown in Figures 5 and 6.







All dimensions are in mm

FIGURE 5. Illustration of the octagonal castellated beams and parent beam

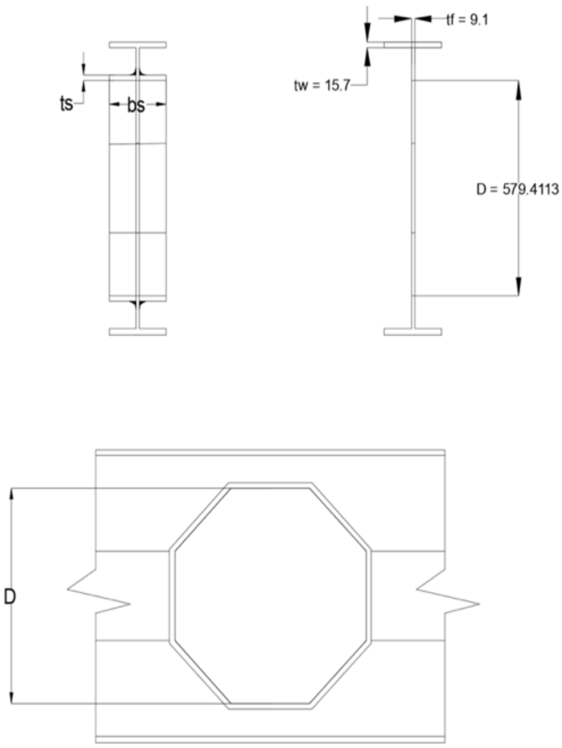
TABLE 1. Details of octagonal castellated beam models

Analysis	Beam Model	L (mm)	n	Width of Stiffener (mm) b_s	Thickness of Stiffener (mm) t_s
	CB 1600-1b-0.25t_f	1600	2	173.20	3.9
1	CB 1600-1b-0.5t_f	1600	2	173.20	7.85
	CB 1600-1b-0.75t_f	1600	2	173.20	11.8
	CB 1600-1b-1t_f	1600	2	173.20	15.7
	CB 1600-0.25b-1t_f	1600	2	43.30	15.7
2	CB 1600-0.5b-1t_f	1600	2	86.60	15.7
	CB 1600-0.75b-1t_f	1600	2	129.90	15.7
	CB 5000-1b-0.25t_f	5000	6	173.20	3.9
1	CB 5000-1b-0.5t_f	5000	6	173.20	7.85
	CB 5000-1b-0.75t_f	5000	6	173.20	11.8
	CB 5000-1b-1t_f	5000	6	173.20	15.7
	CB 5000-0.25b-1t_f	5000	6	43.30	15.7
2	CB 5000-0.5b-1t_f	5000	6	86.60	15.7
	CB 5000-0.75b-1t_f	5000	6	129.90	15.7
	CB 5000-2h	5000	2	173.20	15.7
3	CB 5000-4h	5000	4	173.20	15.7
	CB 5000-6h	5000	6	173.20	15.7

continue...

...cont.

1	CB 8200-1b-0.25t_f	8200	10	173.20	3.9
	CB 8200-1b-0.5t_f	8200	10	173.20	7.85
	CB 8200-1b-0.75t_f	8200	10	173.20	11.8
	CB 8200-1b-1t_f	8200	10	173.20	15.7
2	CB 8200-0.25b-1t_f	8200	10	43.30	15.7
	CB 8200-0.5b-1t_f	8200	10	86.60	15.7
	CB 8200-0.75b-1t_f	8200	10	129.90	15.7
3	CB 8200-2h	8200	2	173.20	15.7
	CB 8200-6h	8200	6	173.20	15.7
	CB 8200-10h	8200	10	173.20	15.7
1	CB 11500-1b-0.25t_f	11500	14	173.20	3.9
	CB 11500-1b-0.5t_f	11500	14	173.20	7.85
	CB 11500-1b-0.75t_f	11500	14	173.20	11.8
	CB 11500-1b-1.0t_f	11500	14	173.20	15.7
2	CB11500-0.25b-1t_f	11500	14	43.30	15.7
	CB11500-0.5b-1t_f	11500	14	86.60	15.7
	CB11500-0.75b-1t_f	11500	14	129.90	15.7
3	CB11500-4h	11500	4	173.20	15.7
	CB11500-8h	11500	8	173.20	15.7
	CB11500-14h	11500	14	173.20	15.7



All dimensions are in mm

FIGURE 6. Illustration of the stiffener

RESULTS AND DISCUSSION

Results of analysis in terms of ultimate load P_u and the strength improvement are tabulated in Table 2. In the table, there are additional eight models (No. 38 to 45) analysed for the intention to highlight the effect of transforming the parent beam (PB) to the corresponding castellated beam (CB) without installation of any stiffeners with regard to failure load.

TABLE 2.Ultimate loads

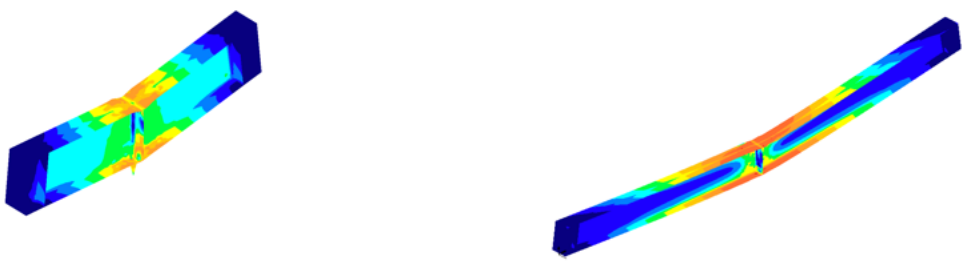
No.	Beam Model	Ultimate Load P_u (kN)	Increment of Strength (%)
1	CB 1600-1b-0.25t_f	640.6	46.52
2	CB 1600-1b-0.5t_f	656.6	50.18
3	CB 1600-1b-0.75t_f	700.7	60.27
4	CB 1600-1b-1t_f	757.8	73.33
5	CB 1600-0.25b-1t_f	645.9	47.74
6	CB 1600-0.5b-1t_f	686.8	57.09
7	CB 1600-0.75b-1t_f	722.8	65.32
8	CB 5000-1b-0.25t_f	474.9	21.36
9	CB 5000-1b-0.5t_f	523.3	33.73
10	CB 5000-1b-0.75t_f	558	42.60
11	CB 5000-1b-1t_f	583.9	49.22
12	CB 5000-0.25b-1t_f	518.1	32.40
13	CB 5000-0.5b-1t_f	534.2	36.52
14	CB 5000-0.75b-1t_f	571.3	46.00
15	CB 5000-2h	416.6	6.47
16	CB 5000-4h	436.4	11.53
17	CB 5000-6h	583.9	49.22
18	CB 8200-1b-0.25t_f	330.9	10.74
19	CB 8200-1b-0.5t_f	352.4	17.94
20	CB 8200-1b-0.75t_f	367.1	22.86
21	CB 8200-1b-1t_f	378.3	26.61
22	CB 8200-0.25b-1t_f	342.7	14.69
23	CB 8200-0.5b-1t_f	369.7	23.73
24	CB 8200-0.75b-1t_f	374.1	25.20
25	CB 8200-2h	347.53	16.3
26	CB 8200-6h	378.3	26.61

continue...

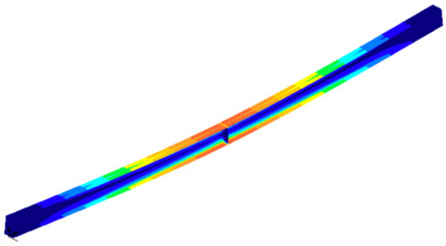
27	CB 8200-10*h*	378.3	26.61
28	CB 11500-1*b*-0.25t_f	237.7	3.98
29	CB 11500-1*b*-0.5t_f	255.6	11.81
30	CB 11500-1*b*-0.75t_f	264	15.49
31	CB 11500-1*b*-1.0t_f	271.1	18.59
32	CB11500-0.25*b*-1t_f	250.8	9.71
33	CB11500-0.5*b*-1t_f	253.8	11.02
34	CB 11500-0.75*b*-1t_f	255.8	11.90
35	CB 11500-4*h*	269.7	17.98
36	CB 11500-8*h*	270.8	18.46
37	CB 11500-14*h*	271.1	18.59
38	PB 1600	842.4	
39	CB 1600	437.2	-48.10
40	PB 5000	266.7	
41	CB 5000	391.3	46.72
42	PB 8200	159.8	
43	CB 8200	298.8	86.98
44	PB 11500	112.8	
45	CB 11500	228.6	102.66

FAILURE MODE AND STRESS ANALYSIS

Transforming a universal beam into octagonal castellated beam may not necessarily give rise to large ultimate capacity. For instance, short span beam CB 1600 has failed far sooner than its parent section PB 1600. This can be attributed to behaviour of stocky beams that largely governed by shear deformation leading to Vierendeel failure. Nevertheless, all other beams show positive increment of strength after transformation to octagonal castellated beams.



(a) (b)



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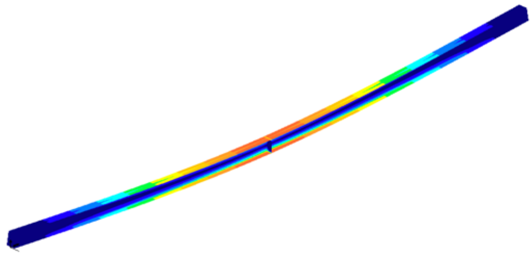
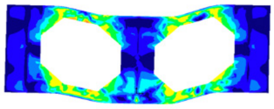


(d)

FIGURE 7. Stress contour in parent beams; (a) PB 1600, (b) PB 5000, (c) PB 8200 (d) PB 11500



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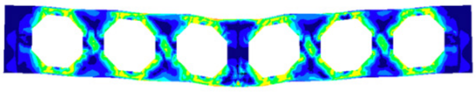

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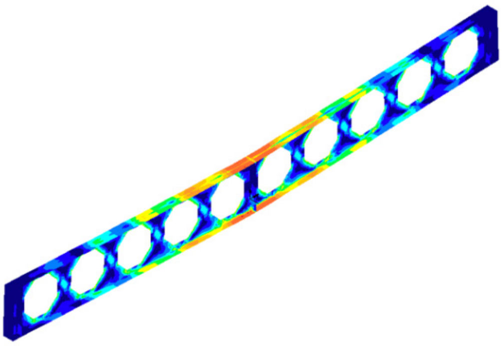

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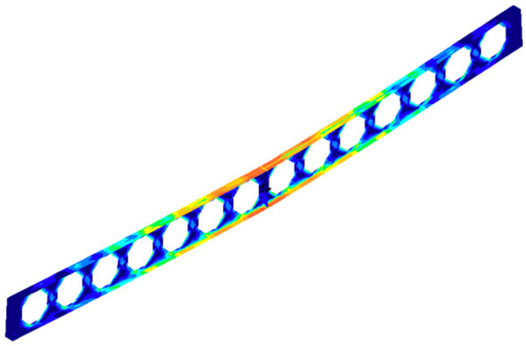


(d)

FIGURE 8. Stress contour in castellated beams; (a) CB 1600, (b) CB 5000, (c) CB 8200 (d) CB 11500

Based on stress concentration pattern shown in Figure 7, all parent universal beams failed in pure flexural mode, regardless the span length. For octagonal castellated beams, however, there are significant stresses concentrated at the corners of the openings especially for short beams CB 1600 and CB 5000. Both beams exhibit Vierendeel mechanism by forming four plastic hinges around the corners of the openings. Such deformation is severe in the openings near the mid-span. Long span beams CB 8200 and CB 11500 show mild stress concentrations at the openings in which the failure is much governed by flexural deformation due to bending moment as indicated by the stress contours in Figure 8.

EFFECTS OF STIFFENER WIDTH

Values in Table 2 shows that the stiffening effect has decreased linearly when the width of the stiffeners was reduced. Stiffeners provided around the openings are proven effective to delay the effect of Vierendeel failure. Use of stiffener width equals 0.25*b* can increase the strength of beam CB 1600 by almost half of its original capacity.

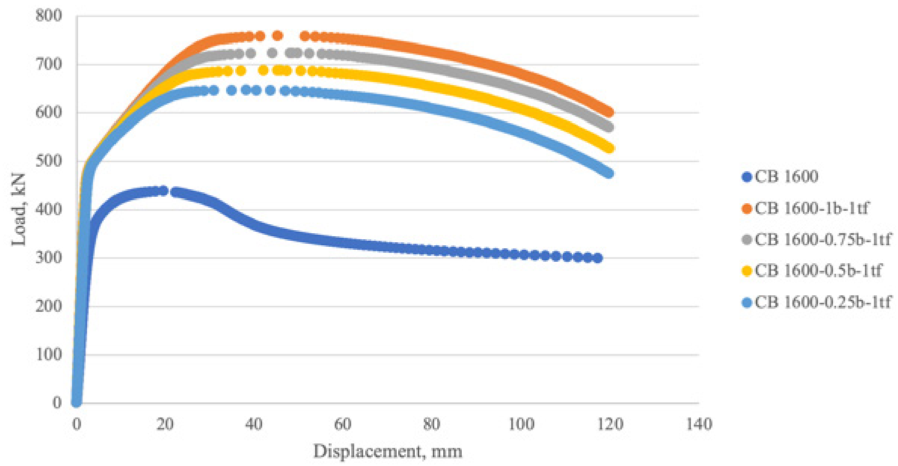


FIGURE 9. Load-displacement relationship of castellated beams CB 1600 (effects of stiffener width)

Load-displacement curves presented in Figure 9 indicate that all stiffened beams exhibit similar behaviour from the initial stage of loadings to the respective failure points. Though the provision of stiffeners is capable to delay failure, they are unable to restore the capacity back to the original value of its parent beam (PB 1600). As far as effect of stiffener width is concerned, short span beam is not suitable to be transformed into octagonal castellated beam.

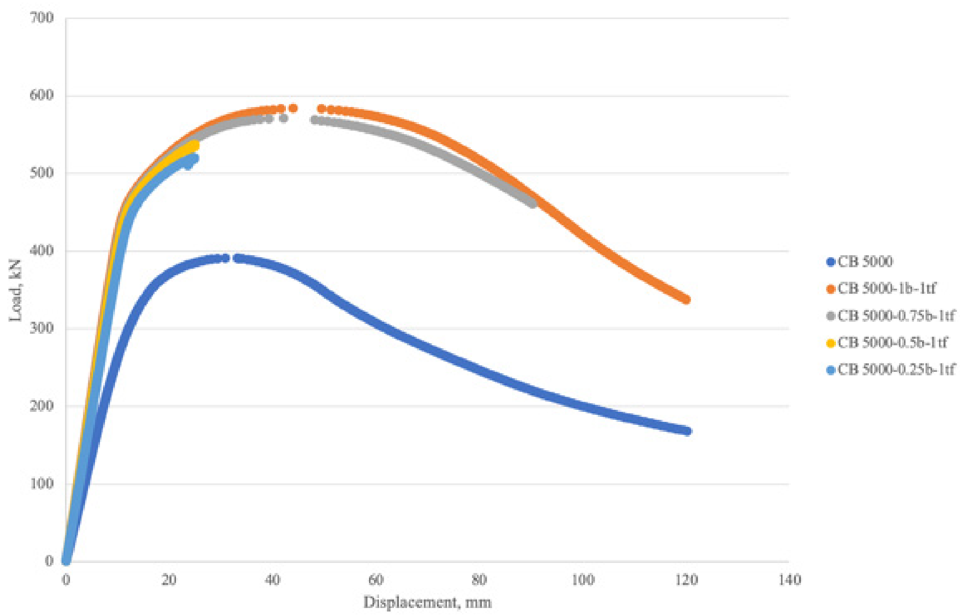


FIGURE 10. Load-displacement relationship of castellated beams CB 5000 (effects of stiffener width)

Provision of stiffeners has improved the ultimate load of beam CB 5000 up to 49%. It is clear from Figure 10 that the non-linear analysis terminated once the beams with stiffeners width of 0.5*b* and 0.25*b* reached their respective ultimate load. This may be attributed to sudden failure of beams due to loss of stiffening effects in CB 5000. To avoid such immediate collapse, provision of stiffeners having at least width of 0.75*b* is recommended. The reason for this is that the stress concentration is of considerably high intensity at the edge of the opening stiffeners as presented in Figure 11. In other beams, the overall behaviour is a combination of shear and bending.

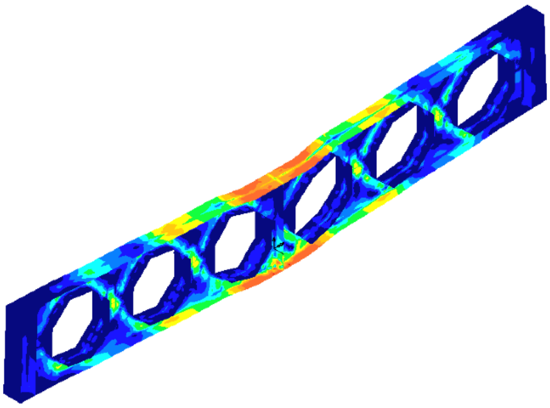


FIGURE 11. Stress concentration in a typical castellated beam CB 5000

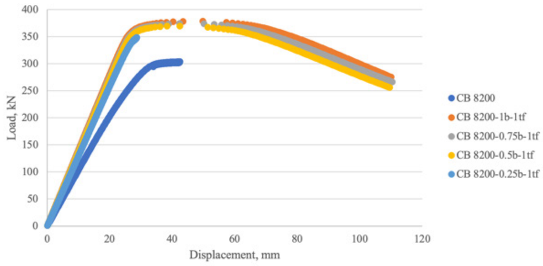


FIGURE 12. Load-displacement relationship of castellated beams CB 8200 (effects of stiffener width)

Figure 12 demonstrates that width of stiffeners equal 0.25*b* in CB 8200 exhibit similar behaviour as in CB 5000 having stiffeners width 0.5*b* and 0.25*b*, thus leading to a conclusion that stiffeners of width at least 0.5*b* is recommended for beams CB 8200. In all cases, they failed in flexural with high compressive and tensile stress intensities at the top and bottom flanges, respectively. Though such stiffeners can increase the ultimate load of CB 8200, the stiffening effects are gradually drop with the increase of span length. Similar phenomenon can also be observed in beams CB 11500 where those beams failed in pure moment failure as shown in Figure 13. The stress concentration around the corners of the openings is not significant.

From Figure 14, it is proven that all beams behave in a similar manner and with almost the same performance. In view of this, provision of stiffeners is not suggested in such long span beams. Instead, use of larger parent beam section might be a better option to enhance the capacity.

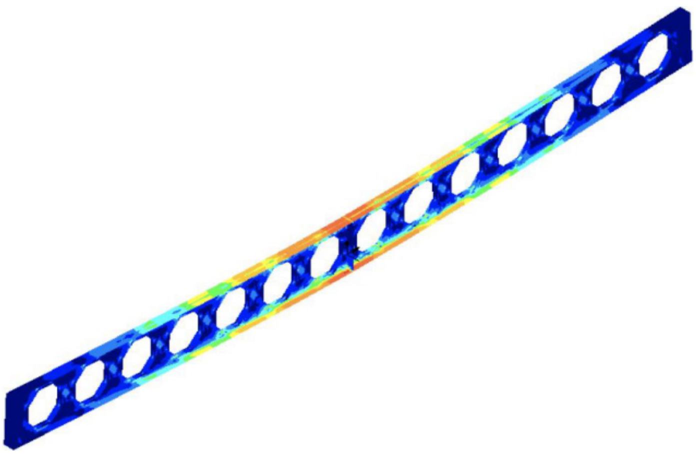


FIGURE 13. Stress concentration in a typical castellated beam CB 11500

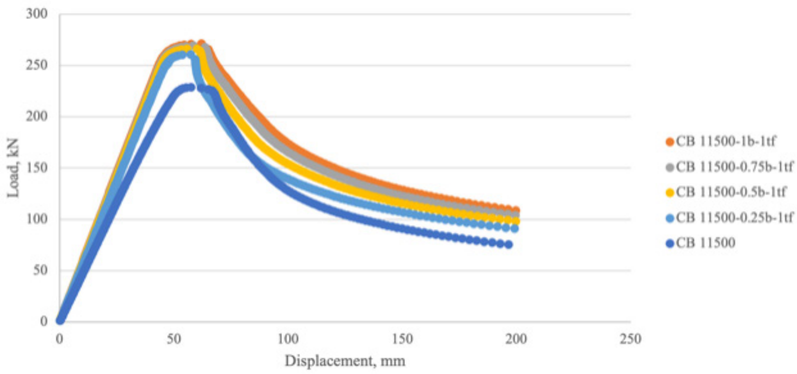
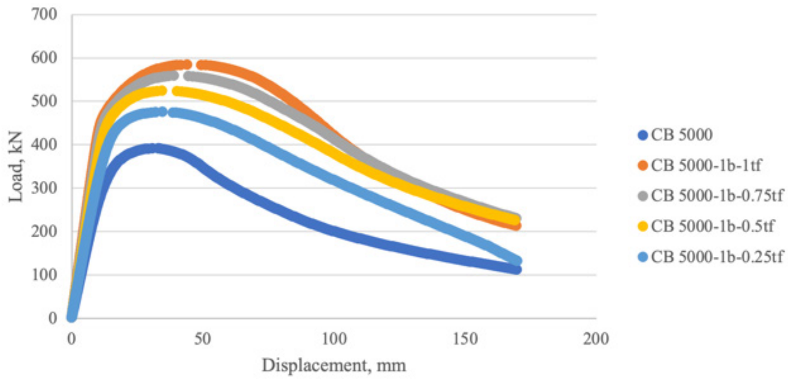


FIGURE 14. Load-displacement relationship of castellated beams CB 11500 (effects of stiffener width)

EFFECTS OF STIFFENER THICKNESS

Thickness of stiffeners is directly proportional to enhancement of ultimate load capacity of octagonal castellated beam. In many cases, the load-displacement relationships show identical behaviour as in the effect of stiffener width. Figure 15 presents the typical relationships for two selected beams i.e., CB 5000 and CB 11500. It is evident from the results that the stiffeners thickness induces much impact than the width with regard to ultimate load. The thickness has also influenced the rise of ductility in each beam such that the deformation undergoes large deflection beyond the maximum capacity, hence sudden collapse is prevented.



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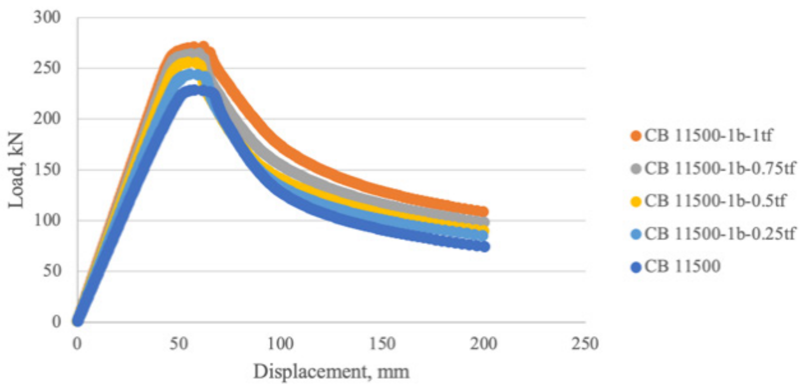


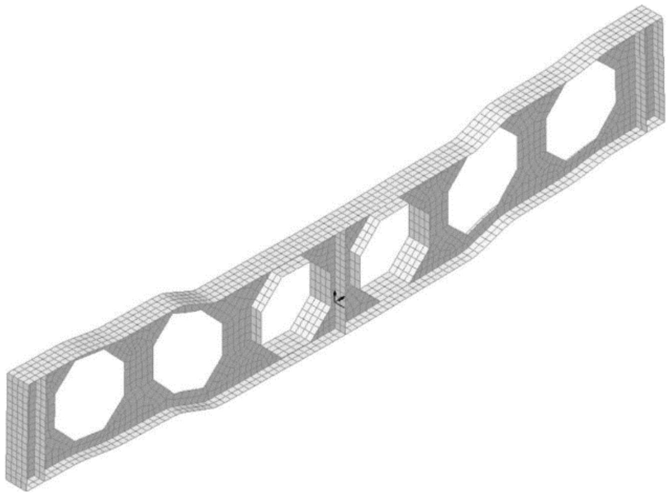
(b)

FIGURE 15. Typical load-displacement relationships of castellated beams (effects of stiffener thickness); (a) CB 5000, (b) CB 11500

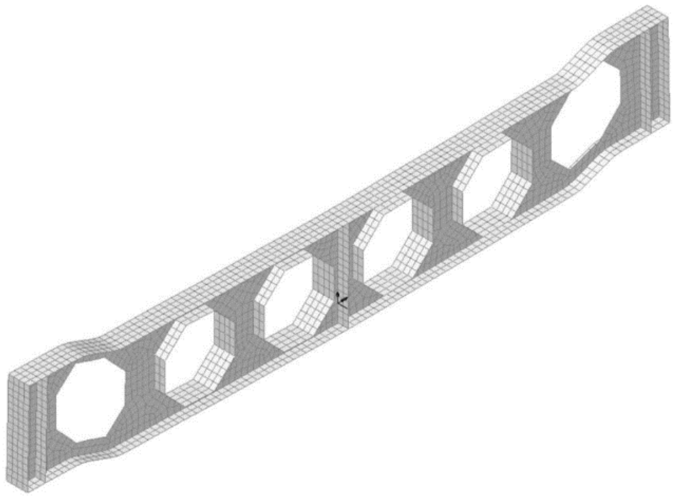
As in previous, installation of stiffeners in long span beam such as CB 11500 does not contribute appreciable strength improvement. Load-deflection curves are close to one another since the initial stages of loadings. This could be due to high bending stresses that limit the effectiveness of the stiffeners, thus dictate the performance.

ARRANGEMENT OF STIFFENERS

Arrangement of stiffeners governs the deformation characteristic of the beams. In the case of CB 5000, stiffening all six openings definitely gives the highest ultimate strength amongst others. As far as deformation is concerned, there are variations resulting from the number of reinforced openings. Figure 16 features typical collapse behaviour of beams CB 5000-2*h* and CB 5000-4*h*. It appears that the top flanges above the reinforced openings remain straight in both cases. This is accompanied by plastic hinges developed at the top and bottom flanges near the unstiffened openings where Vierendeel failure is likely to occur around these regions. Similar characteristics can be observed in CB 8200 and CB 11500 as presented in Figure 17 for typical beams. However, plastic hinges near the unreinforced openings are not clearly visible due to flexural effect.

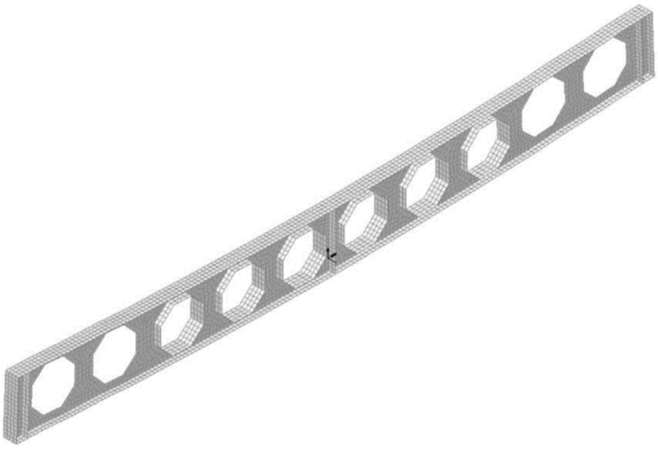


(a)

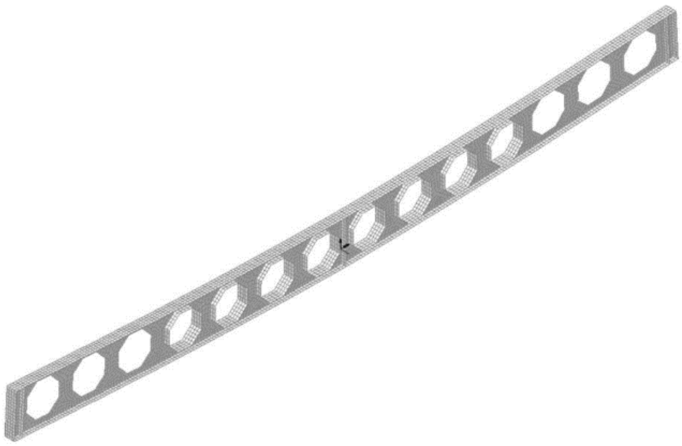


(b)

FIGURE 16. Deformation behaviour; (a) CB 5000-2*h*, (b) CB 5000-4*h*



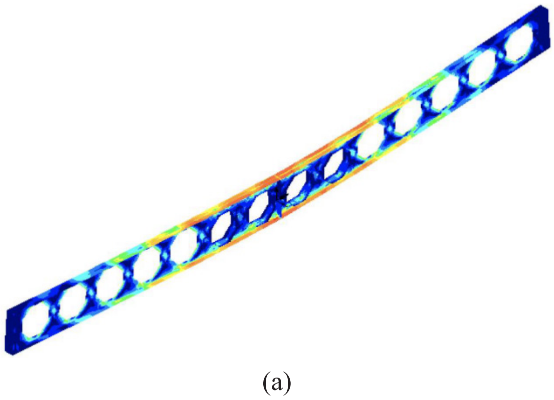
(a)



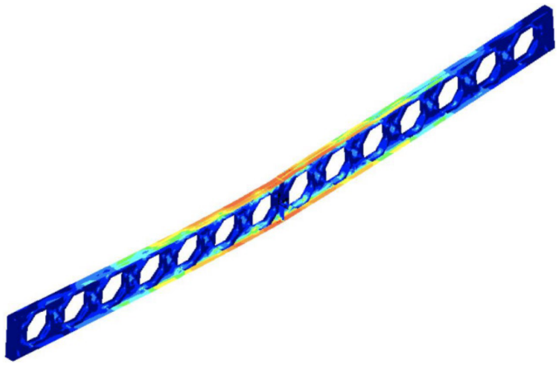
(b)

FIGURE 17. Deformation behaviour; (a) CB 8200-6*h*, (b) CB 11500-8*h*

Apparently in such long span beams, reinforcing all openings serves only marginal difference compared to partly stiffening arrangements. For instance in beams CB 11500, stiffening fourteen openings only provide insignificant raise of ultimate load (about 0.5%) compared to the corresponding beam having four stiffened openings. This reflects high intensity of bending stresses in large span members at the top and bottom fibres that provision of stiffeners for openings particularly those farther away from the point of maximum bending moment is almost negligible, thus unimportant in order to acquire an optimised design. Figure 18 depicts the phenomenon.



(a)



(b)

FIGURE 18. Stresses in fully and partly stiffened long span castellated beams; (a) CB 11500-4*h*, (b) CB 11500-14*h*

WEIGHT-CAPACITY ANALYSIS

With regards to worthiness of providing stiffeners, comparisons can first be made between the parent beams (PB) with the corresponding octagonal castellated members (CB) in terms of strength enhancement and additional material needed as shown in Table 3.

TABLE 3. Weight-capacity analysis of PB and CB

Beam	1600	5000	8200	11500
Strength enhancement (%)	-48.10	46.72	86.98	102.66
Additional Steel Material (%)	11.97	9.59	8.65	8.37

It should be noted that longer span beams gain more benefits from the fabrication to octagonal castellated beams, not only the outstanding performance but also the additional steel plates needed for making up the section is lesser. This suggests the suitability of octagonal castellated beam to be employed in long span constructions.

Table 4 compares the amount of additional materials used for installation of opening stiffeners. It appears that for a particular section of stiffener, the additional steel needed is of same amount when the dimensions are reversed. For example, both beams CB 5000-1b-0.25t_f and CB 5000-0.25b-1t_f require 14.39% additional steel to provide the stiffening material. As far as the ultimate performance is concerned, however, thickness of stiffeners is the governing variable than their width for better gain of ultimate load capacity. For long span beams as in CB 11500, provision of stiffeners may slightly increase the strength but the additional material needed is so much more than the benefit.

TABLE 4. Weight-capacity analysis of stiffened octagonal castellated beams

Beam	Strength enhancement (%)	Additional Steel Material (%)
CB 1600-1b-0.25t_f	46.52	12.28
CB 1600-1b-0.5t_f	50.18	24.57
CB 1600-1b-0.75t_f	60.27	36.85
CB 1600-1b-1.0t_f	73.33	49.14
CB 1600-0.25b-1t_f	47.74	12.28
CB 1600-0.5b-1t_f	57.09	24.57
CB 1600-0.75b-1t_f	65.32	36.85
CB 1600-1b-1t_f	73.33	49.14

continue ...

... cont.

CB 5000-1b-0.25t_f	21.36	14.39
CB 5000-1b-0.5t_f	33.73	28.78
CB 5000-1b-0.75t_f	42.60	43.17
CB 5000-1b-1.0t_f	49.22	57.56
CB 5000-0.25b-1t_f	32.40	14.39
CB 5000-0.5b-1t_f	36.52	28.78
CB 5000-0.75b-1t_f	46.00	43.17
CB 5000-1b-1t_f	49.22	57.56
CB 5000-2h	6.47	19.19
CB 5000-4h	11.53	38.37
CB 5000-6h	49.22	57.56
CB 8200-1b-0.25t_f	10.74	15.30
CB 8200-1b-0.5t_f	17.94	30.59
CB 8200-1b-0.75t_f	22.86	45.89
CB 8200-1b-1.0t_f	26.61	61.18
CB 8200-0.25b-1t_f	14.69	15.30
CB 8200-0.5b-1t_f	23.73	30.59
CB 8200-0.75b-1t_f	25.20	45.89
CB 8200-1b-1t_f	26.61	61.18
CB 8200-2h	16.31	12.24
CB 8200-6h	26.61	36.71
CB 8200-10h	26.61	61.18
CB 11500-1b-0.25t_f	3.98	15.57
CB 11500-1b-0.5t_f	11.81	31.14
CB 11500-1b-0.75t_f	15.49	46.70
CB 11500-1b-1.0t_f	18.59	62.27
CB 11500-0.25b-1t_f	9.71	15.57
CB 11500-0.5b-1t_f	11.02	31.14
CB 11500-0.75b-1t_f	11.90	46.70
CB 11500-1b-1t_f	18.59	62.27
CB 11500-4h	17.98	17.79
CB 11500-8h	12.34	35.58
CB 11500-14h	18.59	62.27

CONCLUSIONS

From the extensive finite element modelling, it can be summarised that not all configurations of parent beams can be fabricated into octagonal castellated beams. Results have shown that it is more beneficial to employ the castellated members in medium or long span constructions concerning the exceptional load carrying capacity they offer with lesser use of additional steel material. For short span beam like CB 1600, drop of strength from the original capacity of its parent beam occurs due to high shear vulnerability of deep web associated with large openings. Use of opening stiffeners is notably effective to enhance the shear resistance of castellated beams up to 73% for the largest span beam and 42% by average. This can be seen in the deformation behaviour of CB 1600 and CB 5000 where both castellated beams exhibit severe Vierendeel mechanism. A slight Vierendeel mode can still be observed with vague plastic hinges in beams CB 8200 and CB 11500 due to the fact that the prominent bending stresses in such long span members have changed the characteristic to pure flexural failure.

Decreasing the stiffeners thickness lower the strength of beams much than decreasing the width. In view of this, it is recommended to stiffen the castellated beams with stiffener flats having thickness of at least half of the flange thickness. Moreover, sudden failure is experienced by CB 5000 and CB 8200. Results of analysis suggest that for beam CB 5000, stiffeners width of at least 0.75*b* should be provided whilst for beam CB 8200, stiffeners width recommended is at least 0.5*b*. Partly reinforcing the openings has demonstrated the redistribution of stress concentration caused predominantly by Vierendeel failure to the unstiffened openings, leading to development of plastic hinges at the region. In long span beams, no appreciable variation of ultimate load is obtained between beam with all openings stiffened and beam with partly stiffening arrangements as a result of flexural effects.

Weight-capacity analysis has proven the benefits gained by long span beams fabricated to castellated form in regards of the excellent strength enhancement and economical use of additional steel material. This again suggests the suitability of octagonal castellated beams to be employed in long span constructions.

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DECLARATION OF COMPETING INTEREST

None

REFERENCES

Al-Thabhawee, H.W. & Mohammed, A.A. 2019. Reinforcing the Octagonal Web Openings of Castellated Beam by Steel Rings. *Al-Qadisiyah Journal for Engineering Sciences* 12(1): 7–16.

Boyer, J.P. 1964. Castellated beams - New developments. *AISC Engineering Journal*: 104–108.

Ellobody, E. 2011. Interaction of buckling modes in castellated steel beams. *Journal of Constructional Steel Research* 67(5): 814–825.

Gandomi, A.H., Tabatabaei, S.M., Moradian, M.H., Radfar, A. & Alavi, A.H. 2011. A new prediction model for the load capacity of castellated steel beams. *Journal of Constructional Steel Research* 67(7): 1096–1105.

Morkhade, S.G., Lokhande, R.S., Gund, U.D., Divate, A.B., Deosarkar, S.S. & Chavan, M.U. 2020. Structural behaviour of castellated steel beams with reinforced web openings. *Asian Journal of Civil Engineering* 21(6): 1067–1078.

Nawar, M.T., Arafa, I.T. & Elhosseiny, O. 2020. Numerical investigation on effective spans ranges of perforated steel beams. *Structures* 25(November 2019): 398–410.

Shanmugam, N.E. & Baskar, K. 2003. Steel–concrete composite plate girders subject to shear loading. *Journal of Structural Engineering* 129(9): 1230–1242.

Wang, P., Ma, Q. & Wang, X. 2014. Investigation on Vierendeel mechanism failure of castellated steel beams with fillet corner web openings. *Engineering Structures* 74: 44–51.