Kufa Journal of Engineering
Vol. 8, No. 1, January 2017, P.P.97-107
Received 12 August 2016, accepted 18 October 2016

EXPERIMANTAL STUDY OF EFFECT OF HEXAGONAL HOLES DIMENSIONS ON ULTIMATE STRENGTH OF CASTELLATED STEEL BEAM

Dr. Hayder Wafi Al-Thabhawee[1]

[1] Lecturer in Civil Engineering Department, College of Engineering, University of Kufa, Dr_haider.wafy@yahoo.com

ABSTRACT

Nowadays, use of castellated steel beams (CSBs) has become very common because of their advantageous implementations in construction of buildings. Castellated Steel Beams (CSBs) are those members that are fabricated from standard hot rolled steel (HRS) I- sections by cutting along its web in "zigzag" pattern and thereafter rejoining the two halves on one another by welding together to form a castellated beam, so that generally the depth of a section will be increased. This research analyses the experimental results of six specimens of castellated steel beams and compares with control beam (Parent section). The purpose of this study is to investigate the effect of hexagonal hole dimensions on the ultimate strength and stiffens response of the castellated steel beam. Also, the effect of number of holes on the behavior of the castellated steel beams that have the same span and ratio of expansion was investigated. All specimens of the castellated steel beam were fabricated from hot rolled steel section (IPE140) and were expanded to (1.56) times the parent section depth. From the test results, it is observed that best dimension of castellated steel beam was (span length to holes space ratio L/S = 8.0); hole depth to Castellated beam depth ratio is h/H=0.56, and hole space to the castellated beam depth ratio is S/H = 1.03. The ultimate strength of the castellated steel beam was increased about (50%) stronger than the original beam.

KEYWORDS: Castellated steel beam (CSB), Virendeel mechanism, Web buckling, ultimate strength, Parent section

دراسة عملية لتأثير ابعاد الفتحات السداسية على التحمل الاقصى للعتبات الفولاذية القلعوية

د. حيدر وفي الذبحاوي

تدريسي في قسم الهندسة المدنية، كلية الهندسة، جامعة الكوفة

الخلاصة

في الوقت الحاضر اصبح استخدام العتبات الفولاذية القلعوية (CSB) منتشرة بشكل واسع نتيجة للإيجابيات المتحققة في انشاء المباني. العتبات الفولاذية القلعوية هي تلك الاعضاء الانشائية التي تصنع من مقاطع حديد قياسية بقطع جذع المقطع بشكل متعرج وبعد ذلك يعاد ربط الشطرين بواسطة اللحام لتشكيل عتبة قلعوية (CB) ونتيجة ذلك سيزداد عمق مقطع العتبة الفولاذية. ان هذا البحث يحلل النتائج العملية لستة عينات من العتبات القلعوية بالاضافة لعتبة معايرة (من المقطع الام). ان هذه الدراسة تهدف لتحري تاثير ابعاد الفتحات السداسية على التحمل الاقصى و سلوك الصلابة للعتبات القلعوية. بالاضافة لذلك تم دراسة تأثير عدد الفتحات على سلوك هذا النوع من العتبات التي تملك نفس الطول و نسبة عمق مختلفة. تم تصنيع جميع العتبات القلعوبة من مقطع قياسي (IPE140) و توسع بالعمق لحد (1.56) بمقدار عمق المقطع الاصلي. بالاعتماد على نتائج الاختبار, نلاحظ ان افضل ابعاد للعتبة القلعوية تكون عند (L/S =8.0) و (H/H=0.56) و (S/H=1.03). التحمل الاقصى للعتبات القلعوية يكون اكبر من تحمل المقطع الاصلي بمقدار (50%).

1. INTRODUCTION

Using steel structures in construction of pre-engineered building (PEB) is becoming widespread due to simplicity and speed of erection in addition to other advantages, such as durability, and strength to weight ratio. However, this type of building has very long spans compare with less loading. In some cases, the standard steel section satisfies the requirement of strength, but does not attain serviceability i.e. deflection criteria. In order to satisfy deflections requirement, it is necessary to increase the depth to span length ratio of beams. Using castellated beams results in increasing in the depth of beams without any increasing in the weight.

The castellated beams are made by separating a standard hot rolled wide flange I-section into two equal parts by cutting the web in a regular alternating zigzag pattern, and then both halves are shifted and rejoined by welding as shown in Fig. 1. The increasing in depth of beam that is obtained due to construction process leads to modify the stiffness and strength of the castellated beam compared to the original I-section beams. In the recent years with the development mechanisms of cutting and welding tools, the castellated beams are manufactured almost in an unlimited number of depths and spans.

The major advantage of the castellated beam is increasing the stiffness and strength of standard I-section beam by increasing its depth without adding any weight. Another advantage of castellated beam which is easing use of functional requirement like ductwork, service pipe, electrical cable, etc. which can be extended into the hexagonal holes, so that the height of floors can be reduced. Also, when used in buildings with exposed members, the hexagonal hole in web gives aesthetic advantage.

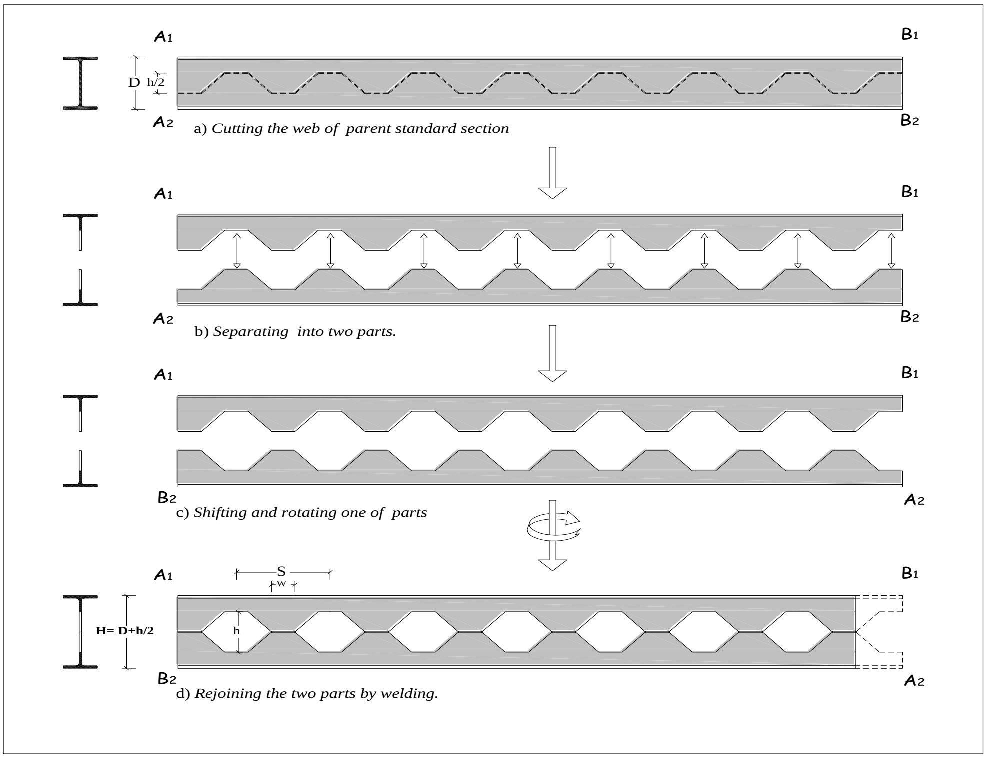

Fig. 1. Fabrication process of castellated steel beam (CSB).

The present research aimed to study the effect of holes dimension on the ultimate strength and stiffness response of the castellated steel beams and compare their experimental results with the original beams (parent section). The effect of dimensions of hexagonal holes have been studied experimentally by dividing the specimens into two groups basing on the number of holes that are eight and six holes as well as control specimen (parent section). Each group included three specimens of same span length with different expanded depth.

2. REVIEW OF PREVIOUS STUDIES

The name of castellated beam is derived from a regular pattern of opening in the web of I-section, because castellated means "built like a castle having regular opens in walls like a castle". In mid-1950s, the castellated beams were commonly used in Europe to decrease the cost of steel structures because of the low ratio of labor cost to material cost (Boyer, 1964).

In 1973, Hosain and Speirs (1973) analyzed experimental results of twelve samples of castellated steel beam to study effect of change numbers of hole on the behavior of beams that have same length of span and ratio of expansion. Also, the effect of hole size on failure mode and ultimate load carried was investigated. The results of experimental test indicated that the best hole size requires a minimum distance of the throat which made the beam less subjected to failure because of Vierendeel mechanism.

Galambos, et al. in (1975) tested five castellated steel beams fabricated from standard section (W10x15) to verify a numerical approach to study the optimum expansion ratio by using elastic and plastic analysis methods. All experimental specimens of castellated beams were subjected to mid-span concentrated loads. The span length of beams were kept constant, but the beam depths were differenced based on variation expansion ratios. The ultimate load capacity were presented but no further discussion about the failure modes was given.

In (2011), Ehab Ellobody (2011) investigated the interaction of buckling modes in castellated steel beams with hexagonal hole experimentally as well as analytically. The author developed 3D finite element model and nonlinear material properties to ninety six model of castellated steel beams by using (ABAQUS) software program. By using nonlinear finite element modeling, the parametric study was carried out to investigate the effects of the variation in geometries of cross-section, span length of beams and steel strength on behavior of castellated steel beam. This study noted that the presence of web distortional buckling causes a significant decrease in the ultimate strength of castellated steel beams. The ultimate load capacity is directly proportional to the steel strength hence offers significantly increase in load failure. It was also noted that normal strength of castellated beam fails in lateral torsional buckling, while high strength of castellated beam fails by web distortional buckling.

In (2012), Wakchaure et al. (2012) used finite element models to study flexural behavior of hexagonal castellated steel beams. The investigation is carried out on castellated beams with two concentrated load and simply boundary condition by using ANSYS software package. From the results of nonlinear finite element model, they are concluded that castellated steel beams were agreeable of serviceability criteria up to a maximum hexagonal opening height in web (60 %) of beam height. Also, since design of longer spans with moderately loaded is controlled by limitation of deflection, the castellated steel beam has demonstrated to be efficient for these cases.

In (2015), Jamadar and Kumbhar (2015) tested experimentally and analytically castellated steel beams using package program ABAQUS ver. 6.13. The castellated steel beams were provided with two type of opening shaped (circular and diamond) by following the recommendation given EUR-Code 3. The analytical results which obtained by using software were validated it by comparing with experimental results. In their paper, it can be seen that the castellated steel beams with diamond opening suffers least amount of local failure as more shear transfer area is available as compared to the castellated steel beams with circular opening. Also, the ultimate load capacity of beams with diamond opening is greater than with circular opening.

3. EXPERIMENTAL PROGRAME

Hot–rolled standard section IPE 140 was chosen as the original section for constructing six specimens of castellated steel beams (CSBs) as well as control beam as seventh specimen. The castellated steel beams (CSB) were fabricated such that three different depth of beams were (218mm), (194mm) and (181mm). Flange thickness was (6,9mm), web thickness was (4.7mm) and span length was (1600mm). The castellation dimensions and notations are shown in Fig. 2. The geometric details and material properties of the parent beam and six castellated beams are summarized in Table (1). Plasma machine is used to cut standard section along its web and re-joint the two pieces by using electrode welding to fabricate a castellated steel beam. The material properties were obtained from tension tests on flat tensile specimens according to ASTM E-8M (1999).

The castellated specimens were divided into two groups based on the number of hexagonal openings. Group1 included three specimens which have eight hexagonal holes, while the remaining three beam specimens which have six hexagonal holes were listed in Group2. In order to avoid any failure modes not required, a transverse stiffeners were installed at mid-span under concentrated forces and at locations of end supports, where all specimens were simply supported.

All specimens were put in test machine with adequate care taken to ensure that beams were correctly placed in the test machine and the mid-span of the beam was in line with the hydraulic jack center line as shown in Fig. 3. All specimens were tested by using load machine of (1000 kN) capacity at Engineering Collage Laboratories of Kufa University.

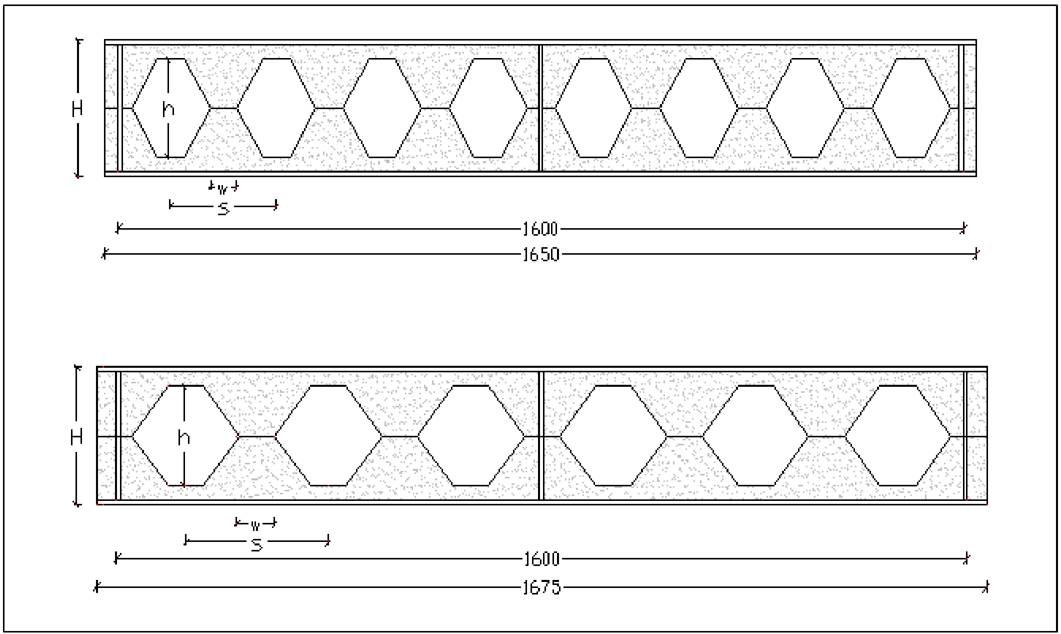

Fig. 2. Dimensions and notation of castellated steel beams specimens.

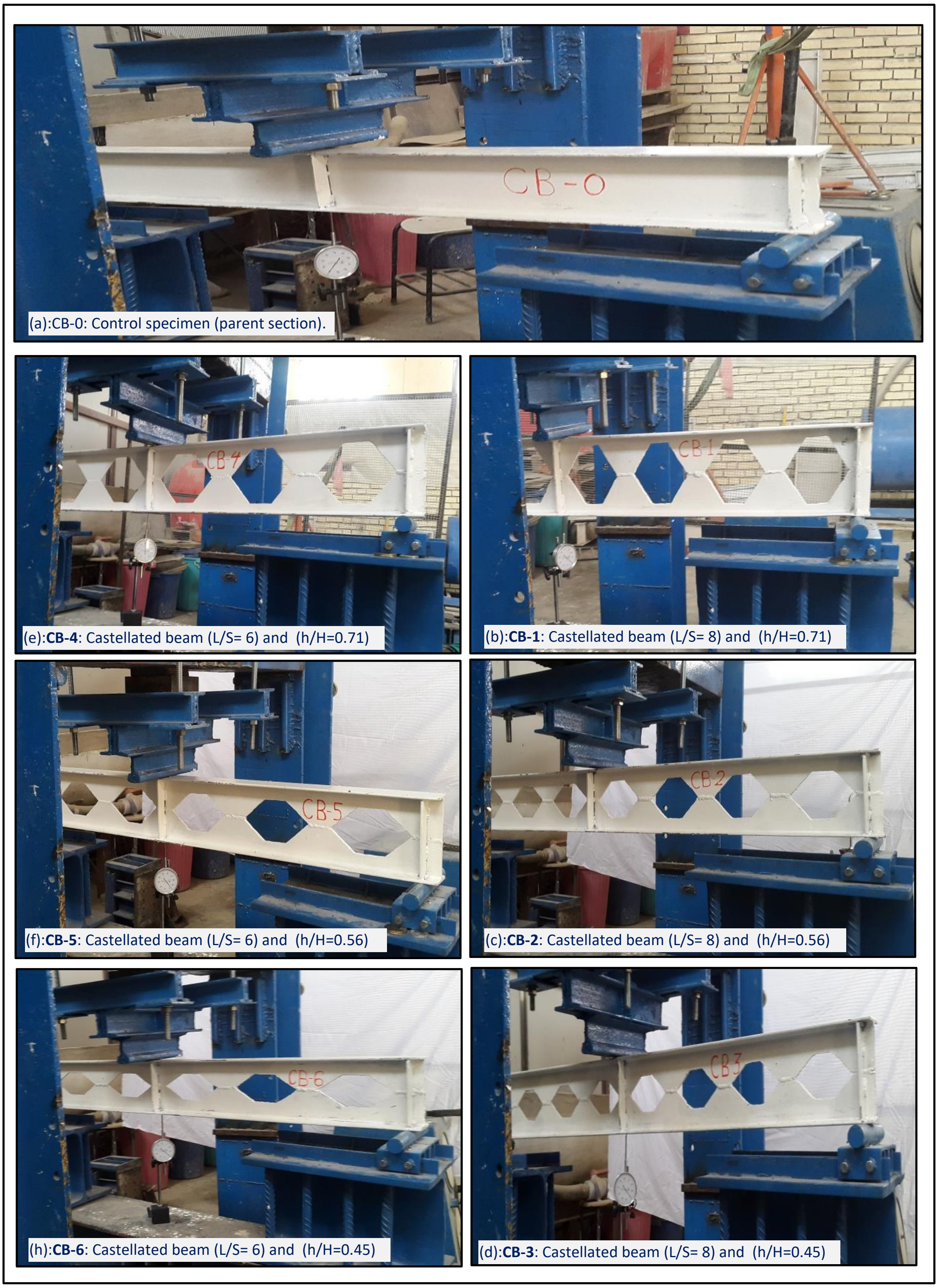

Fig. 3. Test setup.

Table 1. Dimensional and material properties of specimens

Groups	Specimens	Dimensions (mm)				Material Properties (MPa)		
		H	h	S	w	f_y	f_u	E_s
Control	CB-0	140	__	__	__	279	432	2.01×10^5
Group 1	CB-1	218	156	200	50	279	432	2.01×10^5
	CB-2	194	108	200	50			
	CB-3	181	82	200	50			
Group 2	Cb-4	218	156	268	67	279	432	2.01×10^5
	Cb-5	194	108	268	67			
	Cb-6	181	82	268	67			

4. RESULTS DISCUSSION

In order to study behavior of castellated steel beams with different ratios (H/h) and (S/H), seven specimens have been tested as listed in Table (1). The specimens were divide into three groups: the first group contained three specimens of CSBs with ratio of span length to hole space (L/S=8.0) (eight hexagonal holes), the second group included three specimens of CSBs with (L/S = 6.0) six hexagonal holes, and the third group was represented by the parent section (IPE140) as control specimen.

The specimens of CSBs are tested up to failure load. It can be observed that CSBs failed by the formation of four plastic hinges at the re-entrant corners of the hexagonal hole adjacent to the concentrated point load and in the part of the beam where both moment and shear are present. Fig. 4 illustrates a typical failure mode of castellated steel beam.

Fig. 4. Typical failure mode of CSBs.

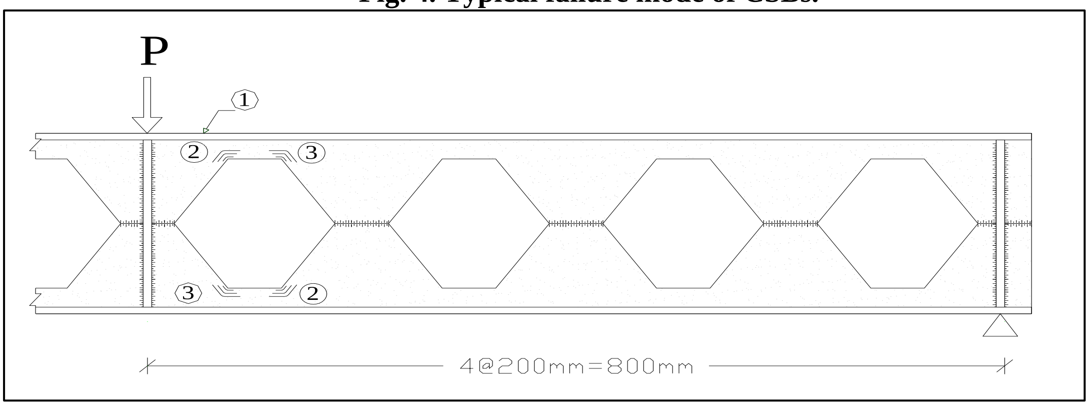

Fig. 5. Yield sequence of CSB specimens for (L/S=8.0).

At ratio of span length to hole space (L/S=8.0), an experimental yielding failure of specimen CB-1 is shown in Fig. 5. The relationship of load–deflection curve for the same specimen (CB-1) as well as control specimen (CB-0) are presented in Fig. 6. At a load about (71.0 kN), It can be shown that first sign of yielding was noticed along the line (1) in Fig. 5. When the test load was raised to (77.5 kN), yielding started first at the hexagonal corners point (2) and then along lines point (3). At these points, the yielding became notable as the tested load was gradually increased and Vierendeel mechanism of failure had occurred when the maximum load of (122.5 kN) was recorded. Web buckling of CSB was occurred in the first panel on the left side of the tested load and after that the specimen started to unload briefly as shown in Fig. 6. The behavior of other specimens of group 1 (CB-2 and CB-3) were similar to that of CB-1 up to the attainment of the failure tested load as shown in Fig. 7 and Fig. 8.

Comparison load – deflection curve of the castellated steel beam results for group1 with eight hexagonal openings (L/S = 8.0) and control specimen (CB-0) was presented in Fig. 9. It appeared from this figure that the ultimate load and stiffness response of the castellated steel beams were significantly increased compare with the original beam (the parent section), but the percentage of increased in strength of castellated beam was variable based on the ratio of beam high to the opening high (H/h). From the result of testing, it was noted that the CSB with height of hole (56%) of its overall height behaves satisfactorily in relation to ultimate load capacity (135.0 kN). In few words, CSBs with (h/H) ratio of (0.56) and (S/H) ratio of (1.03) give more satisfying results than the other specimens as listed in Table (2).

From the experimental result of group 2, which have six hexagonal hole (L/S=6.0), it was shown that CB-6 specimen with height of hole (45%) of its overall height behaves satisfactorily in relation to the ultimate load capacity (111.0 kN) as shown in Table (2). The load-deflection response of CSBs Specimens for group (2) (CB-4, CB-5 and CB-6) was compared with the load-deflection response of original specimen for the parent section (control specimen) as shown in Fig. 10. It can be noticed that failure load and stiffness were significantly increased with the control beam.

Table 2. Results of experimental test

Groups	**Specimens**	**Dimensions (mm)**				**Parametric study**			**Ultimate Load Capacity**
		H	h	S	w	L/S	h/H	S/H	P_{ul} (kN)
Control	CB-0	140	—	—	—	—	—	—	90.5
Group 1	CB-1	218	156	200	50	8	0.71	0.92	122.5
	CB-2	194	108	200	50	8	0.56	1.03	135.0
	CB-3	181	82	200	50	8	0.45	1.10	112.5
Group 2	Cb-4	218	156	268	67	6	0.71	1.23	98.0
	Cb-5	194	108	268	67	6	0.56	1.38	97.0
	Cb-6	181	82	268	67	6	0.45	1.48	111.0

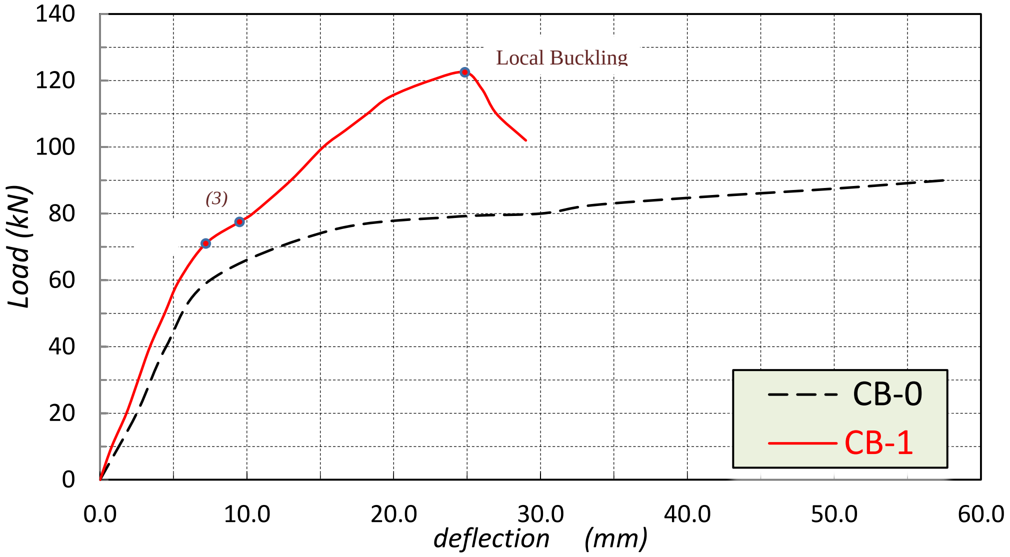

Fig.6. Load –Deflection of specimen (CB-1) and specimen (CB-0).

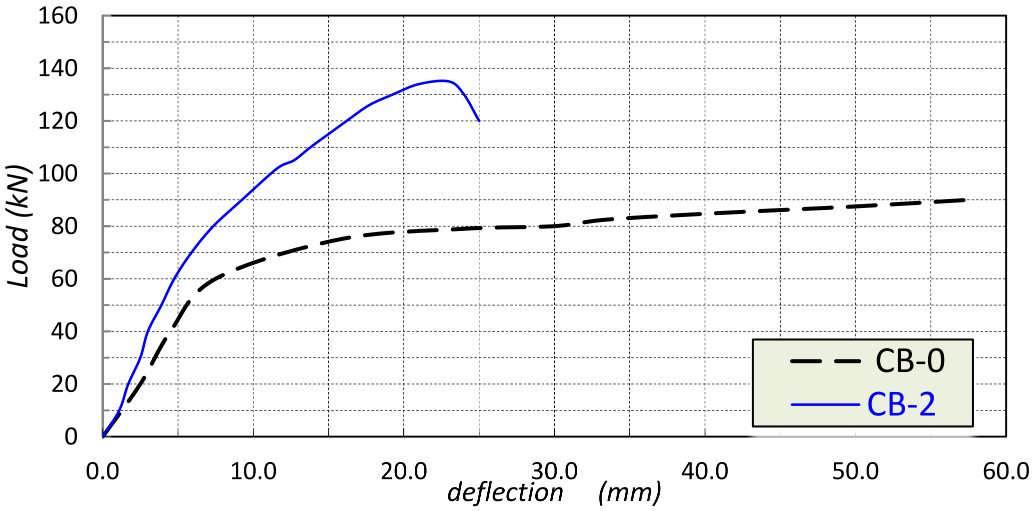

Fig. 7. Load –Deflection of specimen (CB-2) and specimen (CB-0).

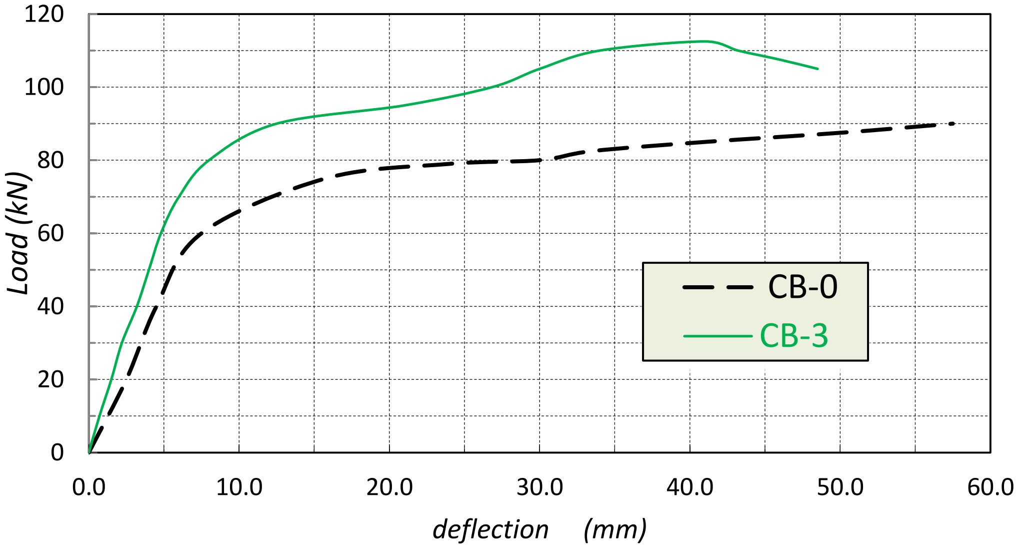

Fig. 8. Load –Deflection of specimen (CB-3) and specimen (CB-0).

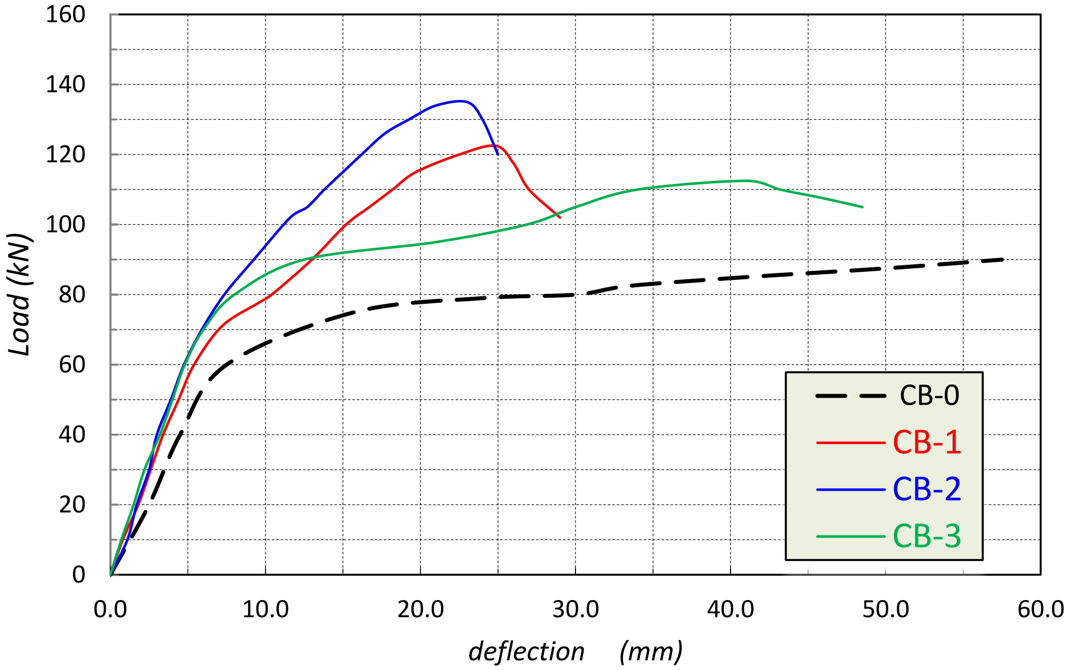

Fig. 9. Load –Deflection of group 1 (CB-1, CB-2, CB-3) and control specimen (CB-0).

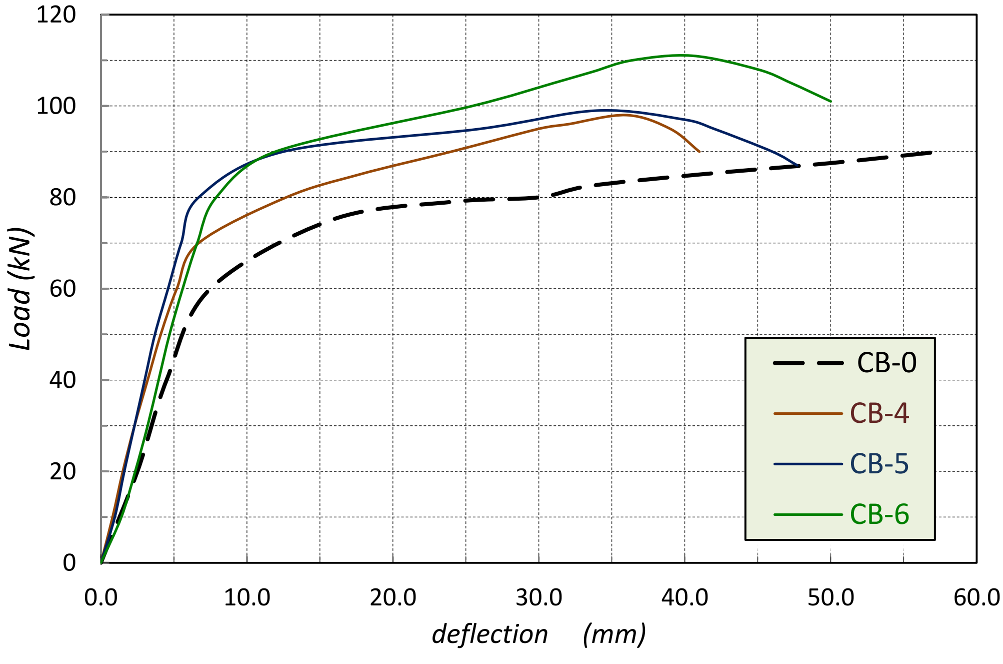

Fig. 10. Load –Deflection curve of group 2 (CB-4, CB-5, CB-6) and control specimen (CB-0).

5. EFFECTE OF HOLES DIMNSIONS ON THE ULTIMATE STRENGTH

In order to find out the optimized dimensions of the castellated steel beams (CSBs), a comparison of the test results of CSBs specimens with control specimen needed to be done. This comparison of the test results for both groups of the castellated steel beams (L/S=8.0) and (L/S=6.0) with different values of (h/H) and (S/H) are given in Table (3). From the results, which listed in Table (3), it is observed that the castellated steel beam (CB-2) with eight hexagonal holes (L/S=8.0) with a depth of hole equal (56%) of the beam depth and (S/H) ratio of (1.03) gave more satisfying results of strength than the other dimension of castellated steel specimens. The percentage of ultimate load capacity of specimen (CB-2) compared with corresponding control specimen (parent section) was increased in (49.2%). The variation of percentage ultimate load of CSBs to ultimate load of original specimen against ratio of (h/H) for group (1) and group (2) was demonstrated in a graphical format in Fig. 11.

Table 3. Comparison of ultimate load of CSBs with control beam

Groups	Spec.	Parametric study			Results		
		L/S	h/H	S/H	P_{UL} (kN)	P_{UL}/P_{OB}	$(P_{UL}-P_{OB})/P_{OB}$
Control	CB-0	—	—	—	90.5	1.0	0.0 %
Group 1	CB-1	8	0.71	0.92	122.5	1.35	35.4 %
	CB-2	8	0.56	1.03	135.0	1.49	49.2 %
	CB-3	8	0.45	1.10	112.5	1.24	24.3 %
Group 2	CB-4	6	0.71	1.23	98.0	1.08	8.3 %
	CB-5	6	0.56	1.38	97.0	1.07	7.2 %
	CB-6	6	0.45	1.48	111.0	1.23	22.7 %

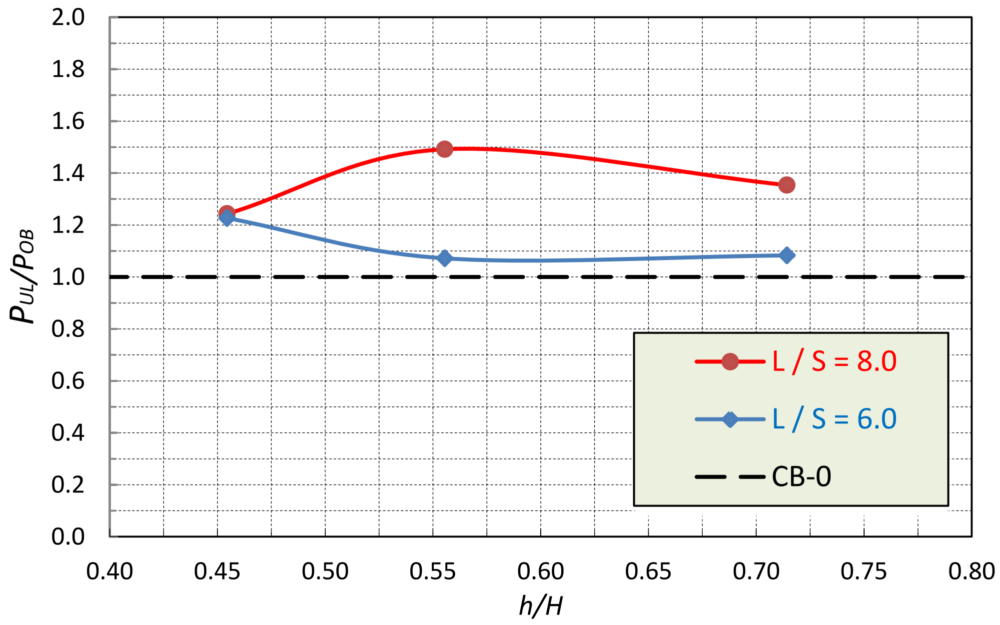

Fig. 11. The relationship between variation in percentage of ultimate load of CSB to original beam (P_{CSB} / P_{OB}) and ratio of high of opening. to. Beam (h/H).

6. CONCLUSION

This investigation has come with the following conclusions:

1) The Experimental results indicated that the castellated steel beam (CSB) with eight hexagonal holes (L/S=8.0) with a depth of hole equal (56%) of beam depth and (S/H) ratio of (1.03) has given more satisfying results of the ultimate strength than the other dimensions of the castellated steel specimens. In few words, It can conclude that the best dimension of the castellated steel beam was (L/S = 8.0), (h/H=0.56), and (S/H = 1.03).
2) According to the test results, the castellated steel beams (CSBs) can be used to modify the strength of the parent I-section by increasing its height without adding any material. The ultimate strength of the castellated steel beam was increased about (50.0%) stronger than the parent I-section.
3) The behavior of the castellated steel beam (CSB) is satisfactory for serviceability criteria because of increasing depth of the castellated steel beam more than the original beam. It increases the depth of the castellated steel beam up to 55.7% deeper than original steel beam.
4) The castellated steel beams (CSBs) are well accepted for using in long span roofing because of its economy and satisfactory serviceability requirement.

7. REFERENCES

ASTM E8M-99. "Standard Test Methods for Tension Testing of Metallic Materials" [Metric], ASTM.

Boyer J. P., "Castellated beam – new developments", AISC National Engineering Conference, AISC Engineering Journal, Vol. 3, pp. 106-108, (1964).

Ehab Ellobody, "Interaction of Buckling Modes in Castellated Steel Beams", Journal of constructional steel research, Vol. 67, pp. 814-825., (2011).

Galambos, A.R., Hosain, M.U., and Spin W.G. "Optimum expansion ratio of castellated steel beams. Engineering Optimization, London, Great Britain, Vol. 1. pp 213- 22s., (1975).

Hosain, M. U. and Speirs, W. G. "Experiments on Castellated Steel Beams", Supplement to the Welding Journal, pp. 329-342, August (1973).

Jamadar A. M. and Kumbhar P.D., "Parametric Study of Castellated Beam with Circular and Diamond Shaped Openings", International Research Journal of Engineering and Technology, Vol.02, pp 715-722., (2015).

Wakchaure M.R., Sagade A.V. and Auti V.A., "Parametric Study of Castellated Beam Varying Depth of Web Opening", International Journal of Scientific and Publications, Vol. 2,pp. 1-5., (2012).