



THE FLEXURAL BEHAVIOR OF COMPOSITE HYBRID CASTELLATED I-BEAM

Kawthar H. Sh. Aljbourey¹ and Najla'a H. Al-Shareef²

¹ **Building and Construction Techniques Engineering Department/College of Engineering and Engineering Technologies/Al-Mustaqbal University/Babylon/Hilla/Iraq. Email: kawthar.hussein.shaaan@uomus.edu.iq**

² **Department of Civil Engineering/University of Babylon/Hilla, Iraq . Email: Eng.najlaa.hameed@uobabylon.edu.iq**

<https://doi.org/10.30572/2018/KJE/160208>

ABSTRACT

This study examines the flexural behavior of six hybrid composite castellated beams with varying castellated degrees (25%, 33.8%, and 50%). Hybrid beams are formed by utilizing plates with different strengths in the compression and tension zones. Three hybrid composite castellated specimens fabricate from half of IPE200 on the bottom and half of IPE160 on the top while the other three hybrid beam fabricate from a half of IPE200 on the upper and half of IPE160 on the bottom. Two symmetric concentrated load were delivered at the third places to the six specimens. It can be seen from the tested beams that the bearing amount decreases by (12% and 37%) with increasing the percentage castellation to (33.8% and 50%) for beams with a noticeable decrease in deflection. Strength augmentation in hybrid beams can be accomplished by incorporating low yield strength steel in the upper T-part of the beam and high yield strength steel in the lower T-part, when under load.

KEYWORDS

Castellated beam, Composite steel concrete beam, Deflection, Hybrid beam, Self-compacting concrete.



1. INTRODUCTION

The hybrid beam is utilized in structural applications to augment its bending capacity. Hybrid beams are formed by using plates of differing strengths in the compression and tension zones. A Castellated Beam is a modified version of a larger beam, achieved by splitting a standard rolled shape into two equal half through a regular alternating pattern of cutting the web. After offsetting one portion to align the high points of the web design, the two pieces are joined together using welding. This results in a castellated beam, which has openings in the web and a greater overall depth compared to a standard I-beam. The increased depth improves the beam's structural performance against bending by 50%. The various shapes of apertures, such as square, rectangular, circular, hexagonal, or octagonal, effectively increase the beam strength without any increasing in weight of the beam. To remedy this problem, it is recommended to incorporate stiffeners around the openings. The types of failure that occur in castellated beams include the rupture of a welded joint in a web post, lateral-torsional buckling of one or multiple web posts, formation of a vierendeel mechanism. A hybrid castellated beam refers to a castellated steel beam with varying grades in the top and bottom zones. This type of beam exhibits superior qualities compared to a homogeneous castellated steel beam.

The increase in the depth of the holes resulted in a decrease of the flexural rigidity of castellated beams (Wakchaure, and Sagade, 2012). Examined the impact of dimensions and distances between hexagonal web openings on steel castellated beams. Employing the finite element technique (FEM), the comparative examination of castellated steel beams has been concluded. Six specimens were created from an IWF segment, each having a unique hole angle of 45°, 50°, 55°, 60°, 65°, and 70°. All variants have apertures with a vertical dimension of 150mm (ho), and the spacing between them varies from 0.05 to 3.15 ho. The specimen that had a 60° angle and a hole distance ranging from 0.186 ho to 0.266 ho yielded the most favorable outcomes according to the FEM study (Budi and Partono ,2017). Utilized the ASTM standards to determine the maximum moment capacity supported by the supplied beam after the process of castellation. The study focused on analyzing the deflection and moment bearing capability of castellated beam sections, such as those with diamond and rectangular openings (Mehetre, and Talikoti). The study impact of castellation on the structural behavior of castellated beams with and without reinforcement. The outcomes were then compared to the data obtained from a solid steel beam. The castellated steel beams had a higher load-carrying capacity than the solid beam and lower midpoint deflection values under normal load (Hadeed and Alshimmeri ,2019). Performed a comprehensive investigation on the structural integrity of steel beams that include openings in the center section. A detailed study was carried out to investigate the behavior of

these special beams. The outcomes show that the load capacity decreases with increasing area and locations of the openings. The parametric study indicated that the center two-thirds of the span is the best location for the web opening (Morkhade and Gupta, 2019). The researchers analyzed two separate boundary conditions in order to assess the impact of apertures on the flexural deflection of beams. They found that the transverse deflection of castellated and cellular beams can be significantly increased by the web shear effect, especially when the beam is relatively short and has a large cross-sectional area (Yuan and et al, 2016). Experimental study was carried out in order to study the structural behavior of steel concrete composite beams with the effect of the compressive strength of concrete slab. The findings demonstrated that the specimens' ultimate moment capacity increased as the concrete's compressive strength increased (Saleh and Fareed, 2018). The study assessed ductility and the flexure strength of hybrid high-performance beams (Wang, 2011). The study conducted experimental and numerical methods were employed to investigate the distortional buckling capacity of hybrid double-I-box beams that were built up-cold-formed (Kulkarni and Gupta, 2018). In 2009, a method was proposed to analyze and calculate the biaxial bending stress in unsymmetrical hybrid beams (Haddock and Razzaq, 2009). Used finite elements to study castellated beam web vertical shear following buckling. Shear buckling factor was strongly affected by web thickness and angle of inclination, according to the study. A more accurate method for estimating castellated steel beams' shear buckling factor was also developed by them (Wang and et al, 2016). Examined the structural components of octagonal web apertures. Instead of employing factory welding, they chose to join the two sides of the parts on site using high strength bolts. A comparative analysis was conducted on web opening elements that were bolted and welded, which revealed that the bolted sections demonstrated significantly enhanced structural performance in contrast to the welded ones (Liu and et al, 2020). Under a concentrated load six experimental castellated steel beam samples' and a control beam was compared. The aim of this investigation was to examine how the size and number of the hexagonal holes effect on the castellated steel beam's maximum strength and stiffness response with identical span and expansion ratio. The optimal dimensions of the castellated steel beam were found to be ($S/H = 1.03$), ($h/H=0.56$), and ($L/S = 8$) (Al-Tabbhawee, 2017).

2. EXPERIMENTAL WORK

2.1. Manufacturing processes

The production process of the castellated beams necessitated the utilization of a specialist CNC cutting machine. Afterwards, the two parts of the steel sections were connected and merged in

a way that created hexagonal compartments in the middle area. Fig. 1 showed specifications and measurements of composite beams produced currently. The dimensions were determined based on the following equations:

$$a = \frac{(D - d)}{\sin 60} \quad (1)$$

$$D = d * (\lambda + 1) * 100 \quad (2)$$

$$h_o = \frac{d - a * \sin 60}{2} \quad (3)$$

Where: h_p =throat depth , a =throat width

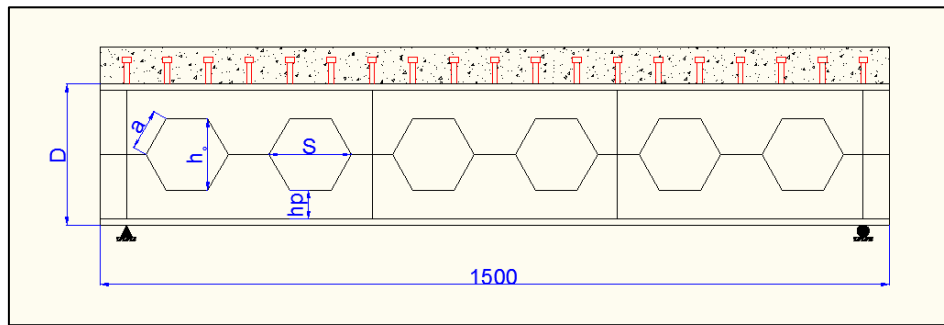


Fig. 1. Specifications and measurements of composite beams produced currently

2.2. Beam Test

Three hybrid composite castellated specimens fabricate from half of IPE200 its dimension ($d=200\text{mm}$, $bf=90\text{mm}$, $tf=11.3\text{ mm}$ and $tw=7.5\text{ mm}$)on the bottom and half of IPE160 its dimension ($d=160\text{mm}$, $bf=74\text{mm}$, $tf=9.5\text{ mm}$ and $tw=6.3\text{ mm}$)on the top with different degrees of castellation $\lambda = (25\%, 33.8\%, \text{ and } 50\%)$ and the other three hybrid composite beam fabricated from half of IPE160 on the bottom and half of IPE200 in the upper part with different degrees of castellation. Two concentrated static loads were symmetrically applied to the third nodes of each of the six specimens. Transverse bearing stiffeners were welded at the third locations of each specimen to offer supplementary support. During the static testing, bearing plates measuring $100 \times 350 \times 10\text{ mm}$ were positioned underneath each load. These plates were specifically built to withstand the highest possible load in order to avoid any potential damage to the concrete caused by localized crushing. The (ACI) was used to design the steel reinforcement for the concrete slab. The design required a single layer of 6 mm distorted bars that were spaced 150 mm apart in both the longitudinal and transverse dimensions. Stud shear connectors, with a shank diameter of 10 mm and a length of 50 mm, were welded in a single array to the midpoint of the top flange. The distance between the connectors and the flange was 77.7 mm. This arrangement was used to create a partial connection. Table 1 displayed the details and measurements of the fabricated specimens. Fig. 2 showed the reinforcement details.

Table 1. The specifications and measurements of the fabricated specimens

Identification	d(mm)	a(mm)	h_o (mm)	h_p (mm)	S(mm)	D(mm)	λ (%)
H1ST	180	51.96	91.23	66.88	101.72	225	25
H2ST	180	70.25	121.31	59.96	141.1	240.84	33.8
H3ST	180	103.92	180.8	44.6	206.4	270	50
H1TS	180	51.96	91.23	66.88	101.72	225	25
H2TS	180	70.25	121.31	59.96	141.1	240.84	33.8
H3TS	180	103.92	180.8	44.6	206.4	270	50

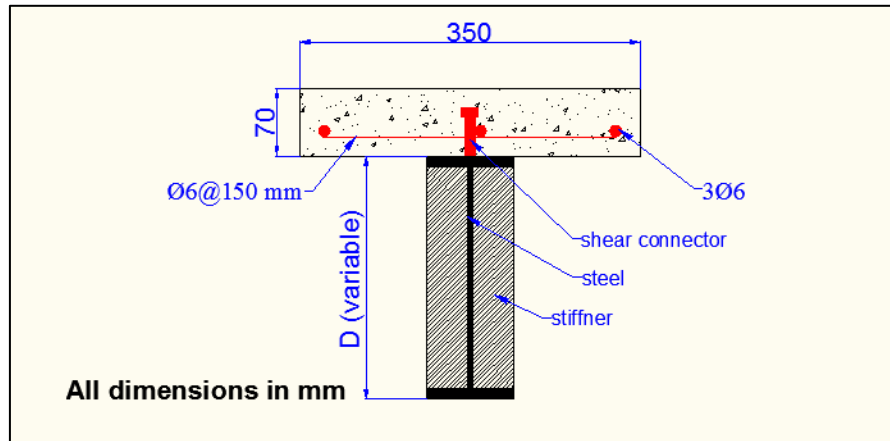
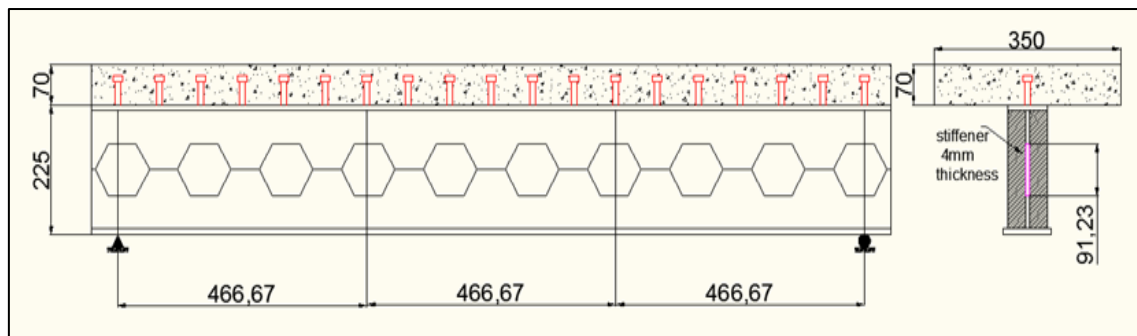
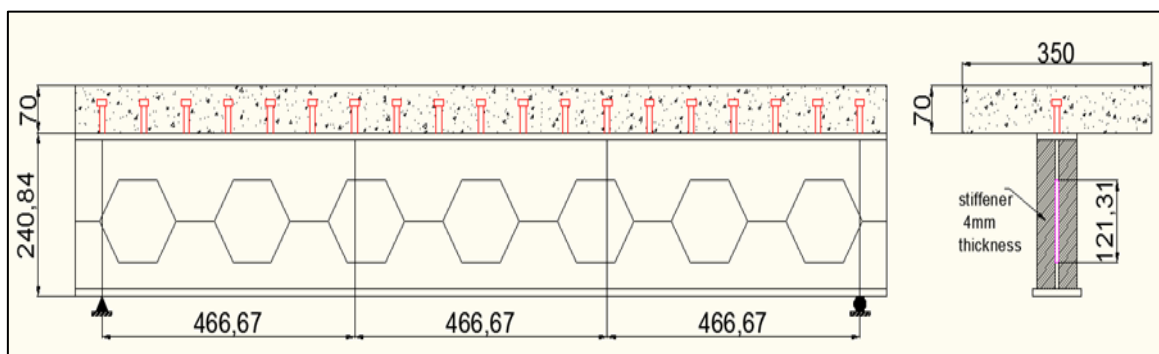
**Fig. 2. Reinforcement details**

Fig.(3 to 5) displayed the specifications and measurements of the hybrid composite beams.

**Fig. 3. The hybrid composite castellated beam's plane ($\lambda=25\%$)****Fig.4. The hybrid composite castellated beam's plane ($\lambda=33.8\%$)**

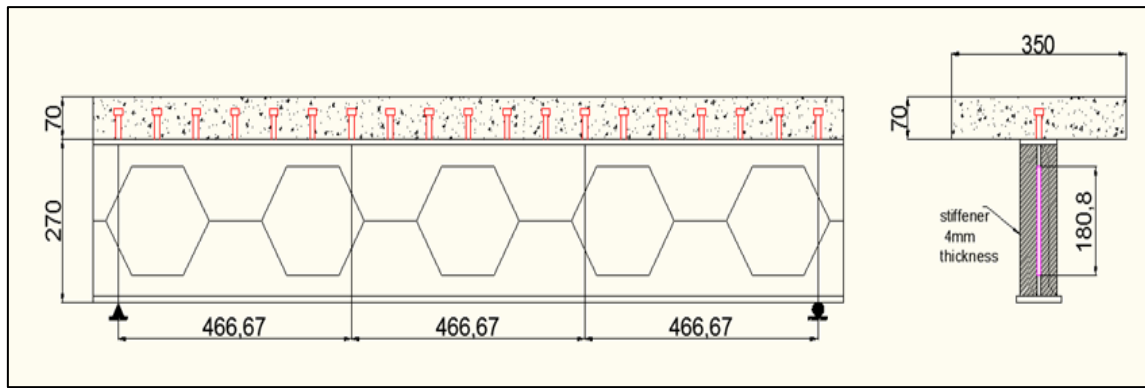


Fig.5.The hybrid composite castellated beam's plane ($\lambda=50\%$)

2.3. Characteristics of steel and concrete elements

Various steel components were employed, such as stiffeners, I-steel beams, reinforcements, and stud connectors. Their characteristics are succinctly presented in Table 3, whereas Table 2 displayed the mechanical properties of concrete.

Table 2. Mechanical characteristics of concrete

Description (Mpa)	Value
f_{cu}	59.44
f_r	5.89
f_{sp}	4.9
E	34000

Table 3. Characteristics of steel elements

Material	Description	Value
Stud connector	length	17 mm
	Shank diameter	10 mm
	Head diameter	50 mm
	Yield strength	447.6 MPa
	Ultimate tensile strength	696.6 MPa
Reinforcement bar	Yield strength	560 MPa
	Ultimate tensile strength	602 MPa
I-beam section (IPE200)	Yield strength	634.93 MPa
	Ultimate tensile strength	825.4 MPa
I-beam section (IPE160)	Yield strength	353.43 MPa
	Ultimate tensile strength	494.82 MPa

2.4. Loading and support condition

The support system consisted of simple supports. All specimens were positioned with one end on a roller and the other end on a hinge. They were then subjected to testing exposed to two concentrated loads at the third span. Fig. 6 showed the load application mechanism. As shown in Fig. 7 dial gauges were positioned at the third point and mid span of the simply supported beams to recorded deflection in these regions.

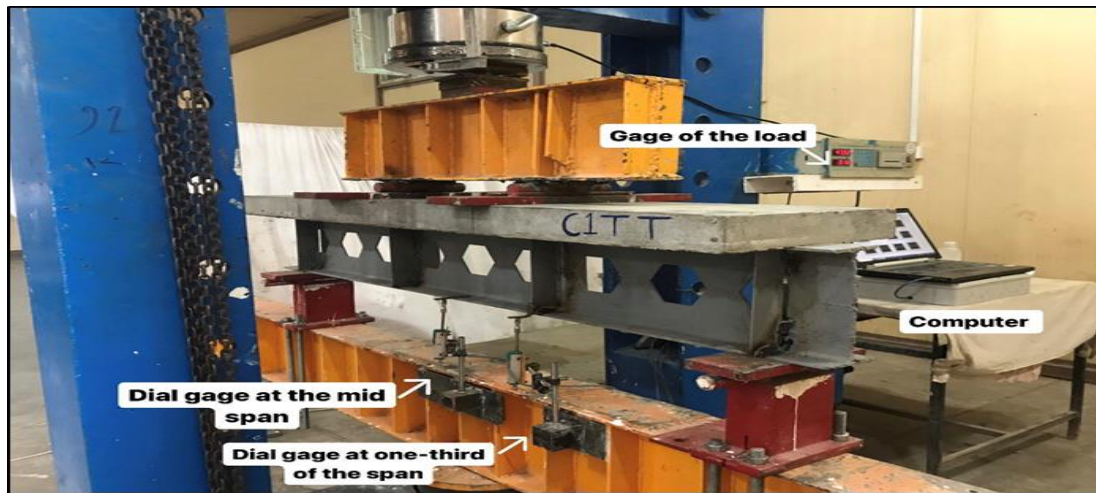


Fig. 6. The load application mechanism

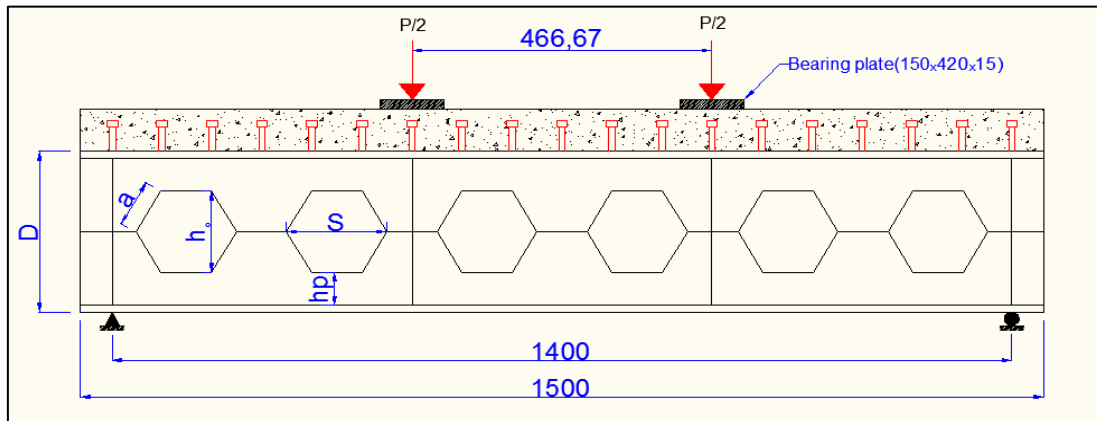


Fig. 7. Dial gages location

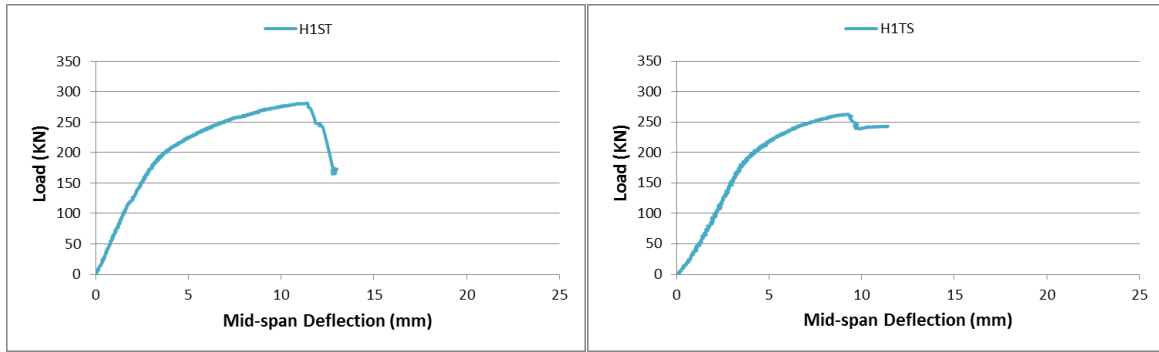
3. THE RESULTS AND DISCUSSION

3.1. Load-deflection relationships

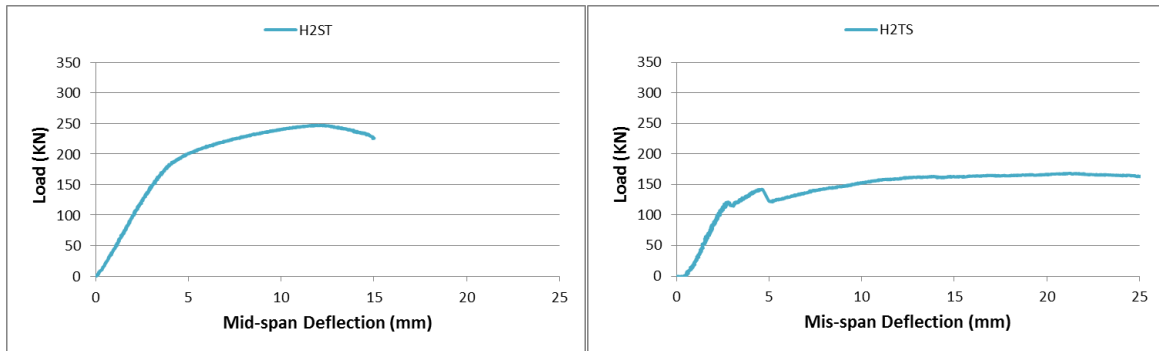
The measurements of the deflection were obtained at the mid span. The load-deflection data for all six specimens at mid-span were recorded and are presented in Fig. 8.

3.2. The effects of castellation

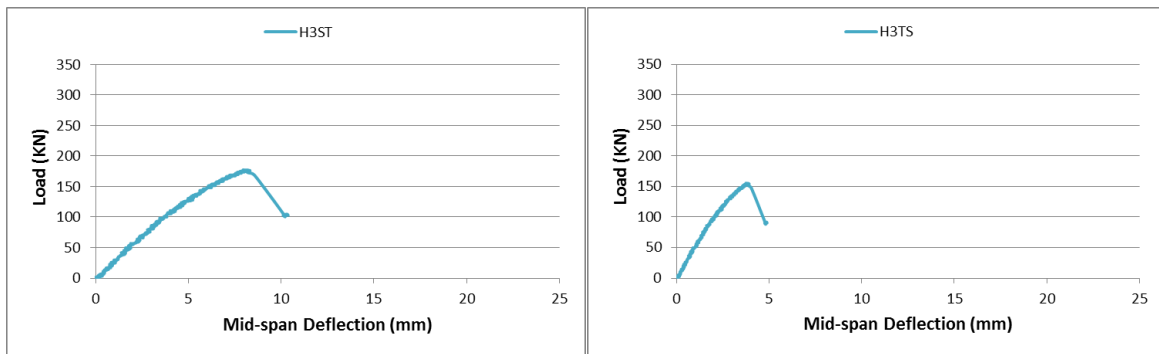
Fig. 9 showed the load–deflection curve for composite castellated beams with percentage castellation equal to (25, 33.8, 50)%. The maximum deflection at ultimate load for H1ST, H2ST and H3ST were 11.4mm, 11.95mm, and 7.96mm, respectively and for H1TS, H2TS and H3TS were 9.28mm, 21.24mm, 3.74. It is evident that increasing the percentage of castellation results in a decrease in the bearing amount for beams with reduced deflection.



a) H1ST ($\lambda=25\%$), H1TS($\lambda=25\%$)

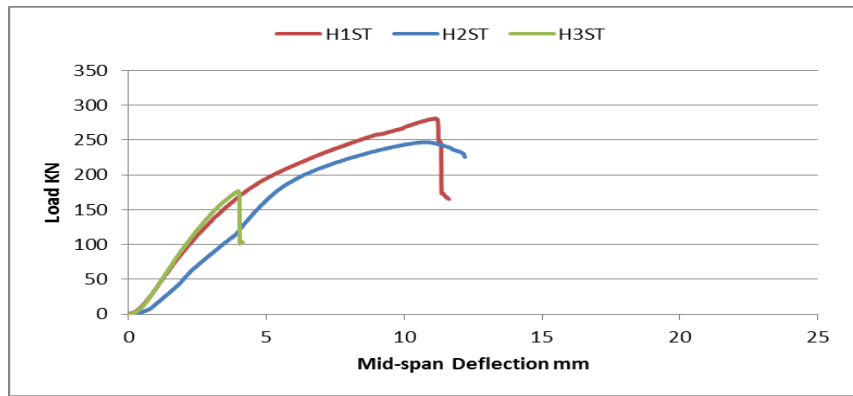


b) H2ST ($\lambda=33.8\%$), H2TS ($\lambda=33.8\%$)

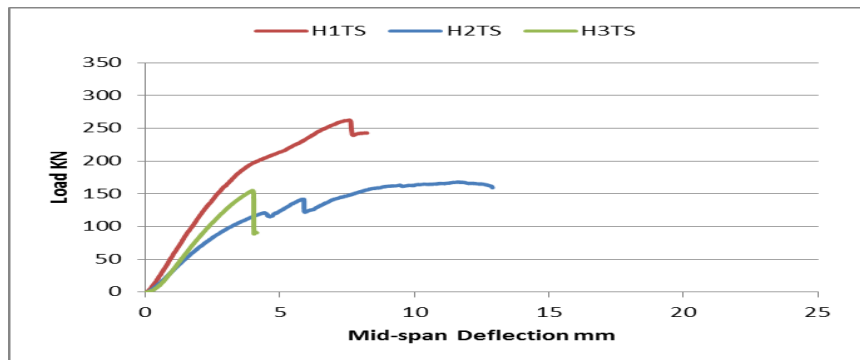


c) H3ST ($\lambda=50\%$), H3TS ($\lambda=50\%$)

Fig. 8. Specimens load-deflection curve of at mid-span.



a)

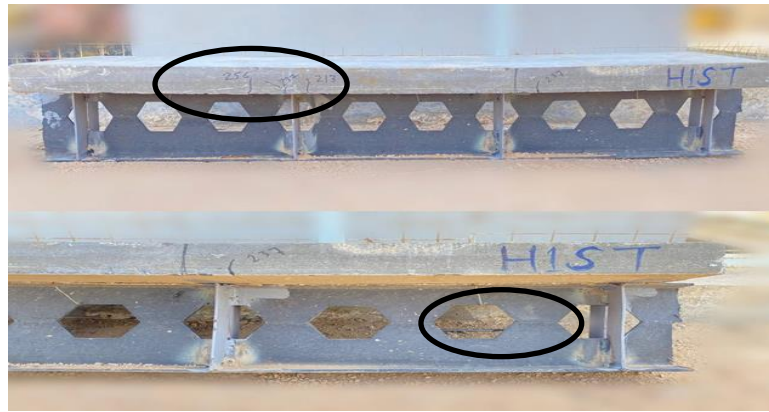


b)

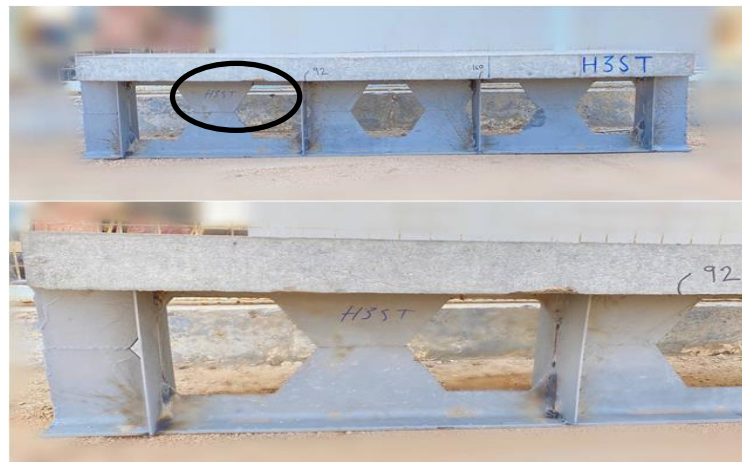
Fig. 9. Comparison in load-deflection curve for all tested beams $\lambda = (25, 33.8, 50) \%$

3.3. Crack pattern and failure mode

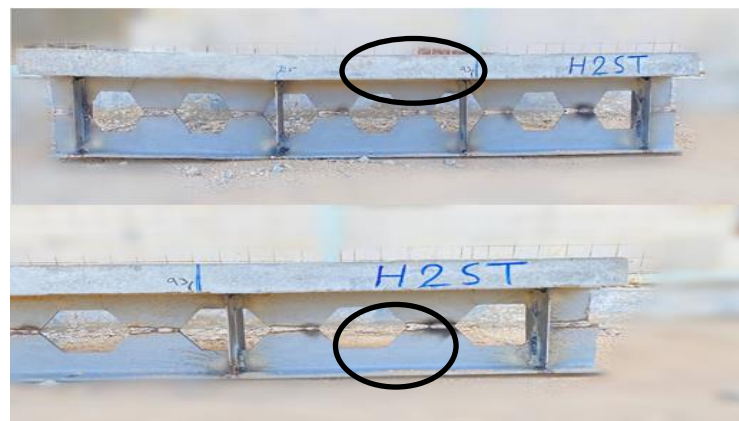
After a period of loading the first crack for specimen H1ST appeared at load equal to 213KN under point load at the left of concrete and after time passed the beam failed by rupture in the joint welding under ultimate load equal to 281.39KN. As for the beam H2ST the first crack appeared at load equal to 93 KN and failed by bending of steel profile at ultimate load equal to 247.34 KN. This beams failed by sudden rupture in the joint welding from left side for H3ST under ultimate load equal to 177.11 KN and the first crack for H3ST appeared at load equal to 92KN. As for the composite beams H1TS, H2TS, H3TS, it was noted that they failed by rupture in the joint welding at ultimate load 262.99 KN, 168.39 KN, 155.35 KN, respectively and the first crack observed at 157KN, 147KN, 127 KN, respectively. Fig. 10 and 11 shows the failure and crack patterns of specimens H1ST, H2ST and H3ST with H1TS, H2TS and H3TS. Table 4. showed the outcomes' of tested beams.



a) Failure of H1ST

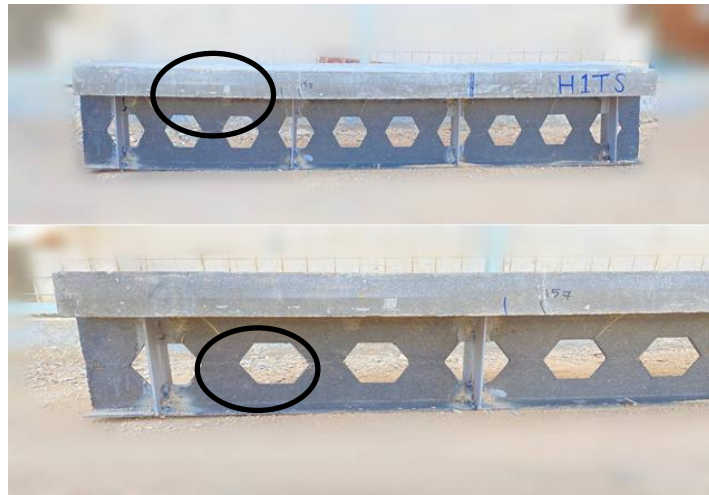


b) Failure of H2ST



c) Failure of H3ST

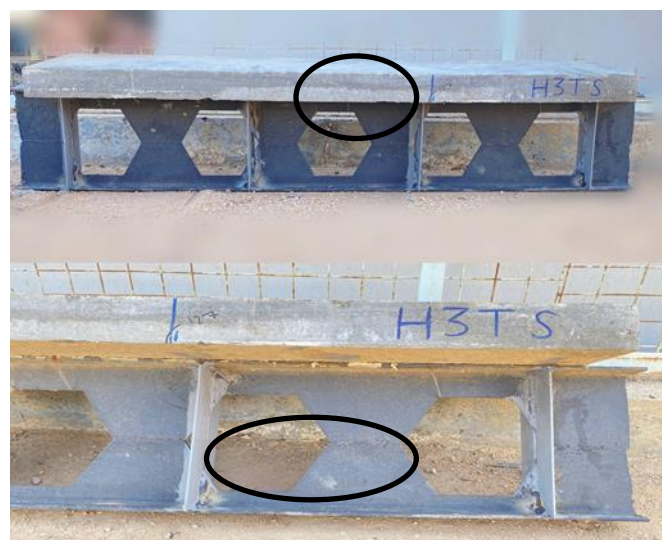
Fig. 10. Failure and crack patterns of specimens



a) Failure of H1TS



b) Failure of H2TS



c) Failure of H3TS

Fig. 11. Failure and crack patterns of specimens

Table 4. The outcomes of the planned specimens' tests

Specimen	First Crack (KN)	Pu (KN)	Deflection (mm)	Failure mode
H1ST	213	281.21	11.40	Rupture in the joint welding
H2ST	93	247.34	11.95	flexural
H3ST	92	177.11	7.96	Rupture in the joint welding
H1TS	157	262.99	9.28	Rupture in the joint welding
H2TS	147	168.39	21.24	Rupture in the joint welding
H3TS	127	155.35	3.74	Rupture in the joint welding

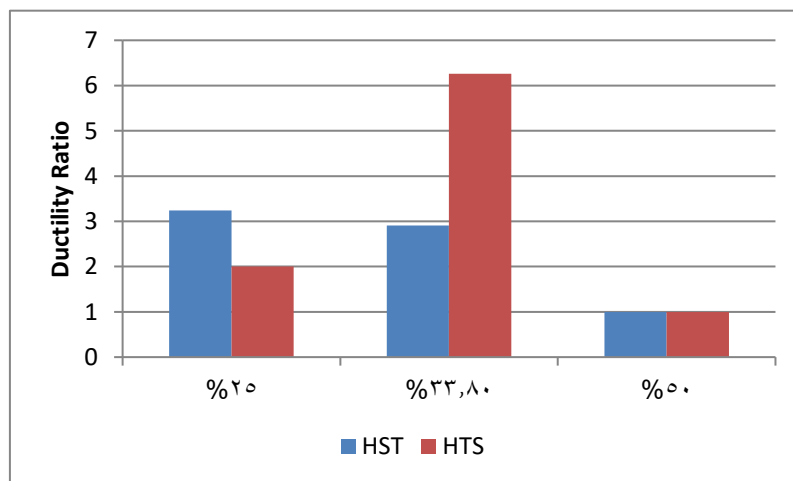
4. DUCTILITY

The ductility of a structure mentions the capacity of the material to undergo plastic deformation when subjected to tensile strain while still being able to bear a load. The ductility factor, denoted as D.I, defines as the ratio of the change in length (Δu) to the change in width (Δy). The current research utilizes the ratio of the vertical displacement at maximum load to the vertical displacement at yield load, denoted as s , to compute the ductility index. The symbol Δy represents the displacement that occurs when the yield load ($P_y = 0.75 P_u$) is applied.

Table 5. lists all beam ductility indexes. A comparison of the ductility index for the tested beam shown in Fig. 12.

Table 5. The ductility ratio values

Specimen	Pu (KN)	Deflection (mm)		Ductility ratio
		Δy	Δu	
H1ST	281.21	3.51	11.40	3.24
H2ST	247.34	4.1	11.95	2.91
H3ST	177.11	7.96	7.96	1
H1TS	262.99	4.62	9.28	2
H2TS	168.39	3.39	21.24	6.26
H3TS	155.35	3.74	3.74	1

**Fig. 12. Comparison of the ductility index for the tested beam.**

4.1. Stiffness

The load necessary to cause a unit of deformation in the member is known as stiffness. The stiffness was calculated as shown in [Tables 6](#). a comparison in stiffness criteria for tested beam shown in [Fig.13](#).

Table 6. The stiffness values

Sample	Ultimate load Pu (KN)	75% Pu (KN)	Max. deflection (mm)	Deflection at 75% Pu (mm)	K' (KN/mm)
H1ST	281.39	211.04	11.40	4.21	50.12
H2ST	247.34	185.51	11.95	4.18	44.38
H3ST	177.11	132.83	7.96	5.24	25.35
H1TS	262.99	197.24	9.28	4.16	47.41
H2TS	168.39	126.29	21.24	3.72	33.94
H3TS	155.35	116.51	3.74	2.52	46.23

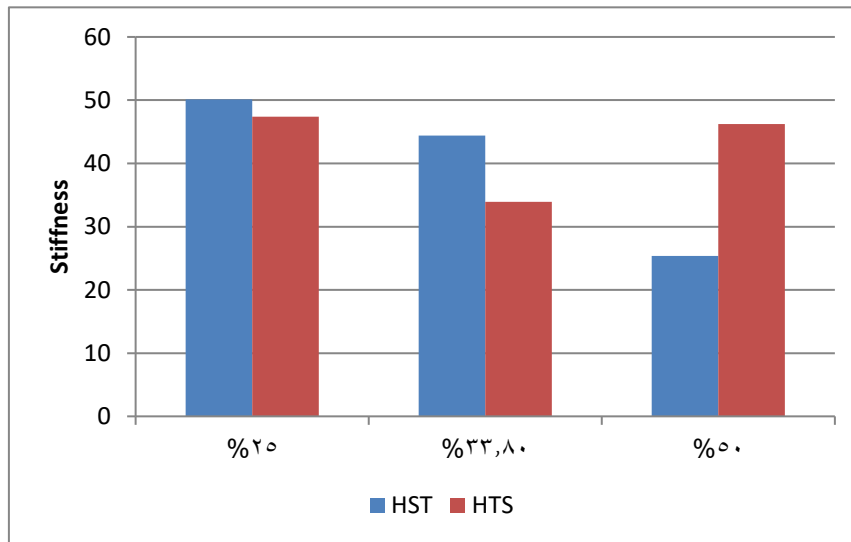


Fig. 13. Comparison of the stiffness for the tested beam.

5. CONCLUSIONS

1. The bearing amount for hybrid beams decreases with increasing the percentage castellation and increase when use low yield strength steel in the upper T-section part of steel.
2. Strength enhancement in hybrid beams might be accomplished by offering upper T-part of the beam with low yield strength steel (LSS) and lower T-part with high yield strength steel (HSS) when subjected to load.
2. It is evident that increasing the percentage of castellation results in a decrease in the bearing amount for beams with reduced deflection.
3. The appearance of the first crack gradually decreases with increasing castellation percentage.
4. A small percentage castellation is stronger in terms of failure.

5. The ductility ratio for hybrid beams evident that increasing the proportion of castellation results in a drop in the ductility ratio for beams.
6. From ductility ratio value for two groups we found that The material's ability to undergo plastic deformation increased when using low yield strength steel in the top T-part with high yield strength steel in the lower T-part .
7. The use of a composite castellated beam with a hybrid I-section featuring low-strength steel in the top part and high-strength steel in the bottom part provides a balanced approach to optimizing both ductility and stiffness.
8. Using low-strength steel in less critical areas reduces costs while still achieving adequate performance. High-strength steel in key load-bearing regions ensures that the beam meets strength requirements without excessive material use.
9. It can be seen from the tested beams that the bearing amount decreases by (12% and 37%) with increasing the percentage castellation to (33.8% and 50%) for beams with a noticeable decrease in deflection.

6. REFERENCES

- ACI (American Concrete Institute). (2014). ACI 318-14. Building code requirements for structural concrete.
- Al-Thabhwawee, H. W. (2017). Experimental Study of Effect of Hexagonal Holes Dimensions on Ultimate Strength of Castellated Steel Beam. *Kufa Journal of Engineering*, 8(1), 97-107.
- Budi, L., & Partono, W. (2017). Optimization analysis of size and distance of hexagonal hole in castellated steel beams. *Procedia engineering*, 171, 1092-1099.
- Haddock, R. C., & Razzaq, Z. (2009). Calculating bending stresses in an unsymmetrical hybrid beam. *Practice Periodical on Structural Design and Construction*, 14(4), 214-218.
- Hadeed, S. M., & Alshimmeri, A. J. H. (2019). Comparative study of structural behaviour for rolled and castellated steel beams with different strengthening techniques. *Civil Engineering Journal*, 5(6), 1384-1394.
- Kulkarni, A. S., & Gupta, L. M. (2018). Experimental investigation on flexural response of hybrid steel plate girder. *KSCE Journal of Civil Engineering*, 22, 2502-2519.
- Liu, M., Liang, M., Ma, Q., Wang, P., & Ma, C. (2020). Web-post buckling of bolted castellated steel beam with octagonal web openings. *Journal of Constructional Steel Research*, 164, 105794.

- Mehetre, A. J., & Talikoti, R. S. Analytical and Experimental Investigation of Castellated Beam by American Standard. *Journal of Engineering Research and Application* ISSN, 2248-9622.
- Morkhade, S. G., & Gupta, L. M. (2019). Ultimate load behaviour of steel beams with web openings. *Australian Journal of Structural Engineering*, 20(2), 124-133.
- Saleh, S., & Fareed H. AlMosawi, F. H. A. (2018). Behavior of Steel-Normal And High Strength Concrete Composite Beams With Partial Shear Interaction behavior of Steel-Normal And High Strength Concrete Composite Beams With Partial Shear Interaction. *Kufa Journal of Engineering*, 9(1), 175–190.
- Wakchaure, M. R., & Sagade, A. V. (2012). Finite element analysis of castellated steel beam. *International Journal of Engineering and Innovative Technology*, 2(1), 365-370.
- Wang, C. S., Duan, L., Wei, M., Liu, L. X., & Hu, J. Y. (2011). Bending behavior of hybrid high performance steel beams. *Advanced Materials Research*, 163, 492-495.
- Wang, P., Guo, K., Liu, M., & Zhang, L. (2016). Shear buckling strengths of web-posts in a castellated steel beam with hexagonal web openings. *Journal of Constructional Steel Research*, 121, 173-184.
- Yuan, W. B., Yu, N. T., Bao, Z. S., & Wu, L. P. (2016). Deflection of castellated beams subjected to uniformly distributed transverse loading. *International Journal of Steel Structures*, 16, 813-821.