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Behavior of Concrete Beam Encasing Castellated Steel Section with Different Opening Size

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ABSTRACT

This research aims to investigate the behavior of castellated steel sections with varying hole sizes enclosed in a concrete beam. Should two different opening size types (depth 140mm and depth 280mm) be used? When we use two types of shear connectors with full and partial interaction, stud connections integrate the steel and concrete parts. This research demonstrates We examined five simply-supported composite beams under two-point loading conditions. We constructed four examples using castellated steel beams, and produced one specimen using standard steel beams as a control. We examine the maximum load support capacity. Examined are the specimens of composite beams' deformations. Among the many characteristics assessed are the castellated beam size of the aperture and the whole and partial composite interactions. According to test results, the sample had a 140mm hexagonal hole. The sample experienced an increase in final load percentages of approximately 11.11%. Compared to the sample featuring a 280mm hexagonal opening size, the mid-deflection and horizontal displacement showed a significant increase. The figures indicate a final load of approximately 18.82% and 16.7%, respectively. Full interaction also revealed a higher ultimate load for the sample with the same aperture. When the sample was fitted with a 140mm hexagonal hole, the percentages increased by approximately 6%. Additionally, the percentage of deflection at midspan and the percentage of horizontal displacement decreased by approximately 16.7% and 26.8%, respectively, compared to the sample with a hexagonal opening size of 280 mm.

1. Introduction

It is essential for civil engineers designing high-rise buildings and substantial infrastructure subjected to various structural loads to consider the flexural capacity and deflection of structural elements along with other deterioration factors [1]. Similar to other structural components, beams endure substantial stresses and are susceptible to deflection and deformation if inadequately constructed [2]. Consequently, academics and civil engineers have focused on investigating the influence of forms and materials used in beams to achieve optimal strength [3]. Researchers have worked hard to create new procedures to improve the structural performance and construction of building components. One of the most recent innovations that may be used in building construction is the use of Castellated beams [4]. The project's intended needs dictate the division of the beam's web along its midline into a zigzag or rack-shaped pattern. Following a shift in half-pitch, the two halves fuse together. Reuniting the two pieces creates a deeper measurement for the beam while maintaining its weight. The transformation of a steel beam into this shape is believed to enhance its strength, stiffness, and potential for significant lengthening. Additionally, it would let services like plumbing and electricity pass

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through the bay's holes. The primary downside would be the manufacturing cost [5, 6]. Concrete encasing may be used to transform cassel-shaped beams into composite structural beams. [7] The author investigated the structural performance of composite castellated beams with various web opening sections. By varying the aperture, the author hoped to determine the maximum load-carrying capacity and deflection. The results demonstrated that composite beams with 140 mm openings had the best carrying capacity and the least amount of deflection when compared to those with hexagonal openings (opening sizes of 280 mm).

2. Experimental Part

2.1 Production of the Castellated Steel Division

Composite and non-composite built-up castellated steel beams have garnered little scholarly attention. Concrete with composite castellated steel encasement has been the focus of even fewer studies. There is little investigation in the existing literature. A longitudinal zigzag pattern inclines the centerline of a rolled steel I beam to fabricate castellated steel beams. The cutting method used a Computer Numerical Control (CNC) plasma machine to produce holes with a precise and uniform shape. Following the cutting procedure, we separated and realigned the two beam segments to enable uninterrupted electric welding of the web configuration's apexes, creating a castellated steel I-section. This enhanced the section modulus of the new section and augmented its bending stiffness relative to the root-rolled I-beam steel section by elevating the overall height of the beam.

2.2 Specifications and size of samples

As part of the investigation into the mechanical characteristics of the steel section, we cut three specimens to evaluate the yield, ultimate tensile strength, and elastic modulus for the castellated beam. We categorize and count the specimens Table 1 . Table 2 includes the castellated cross-section in which the steel beam is (200 mm×100 mm×21.3kg/m) According to the ASTM E8/E8M-15a[8] standard. Figure 1 displays the whole designations and information of the examined specimens.

Table 1. Classes for Specimens

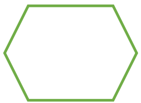
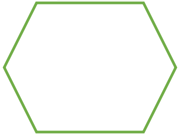
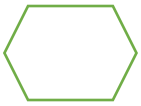
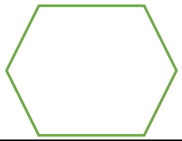
Specimen No.	Designation of the specimen	Description	Size of opening
1	NSC0F00	Composite castellated beam encasing with normal strength concrete on each section, sold, and Full interaction.	No opening
2	NSCHF35	Composite castellated beam encasing with normal strength concrete on each section, opening hexagonal and Full interaction.	size 140mm 
3	NSCHF70	Composite castellated beam encasing with normal strength concrete on each section, opening hexagonal and Full interaction.	size 280mm 
4	NSCHP35	Composite castellated beam encasing with normal strength concrete on each section, opening hexagonal and Partial interaction (70% of full).	size140mm 
5	NSCHP70	Composite castellated beam encasing with normal strength concrete on each section, opening hexagonal and Partial interaction (70% of full).	size 280mm 

Table 2 . Steel sections' mechanical characteristics and geometric arrangement

Flange (mm)		**Web (mm)**		**Ec (GPa)**	**Fy (MPa)**	**Ultimate Strength fu (MPa)**
wid	**Thic**	**H**	**Thic**			
100	8	184	5.5	207.0	376	517

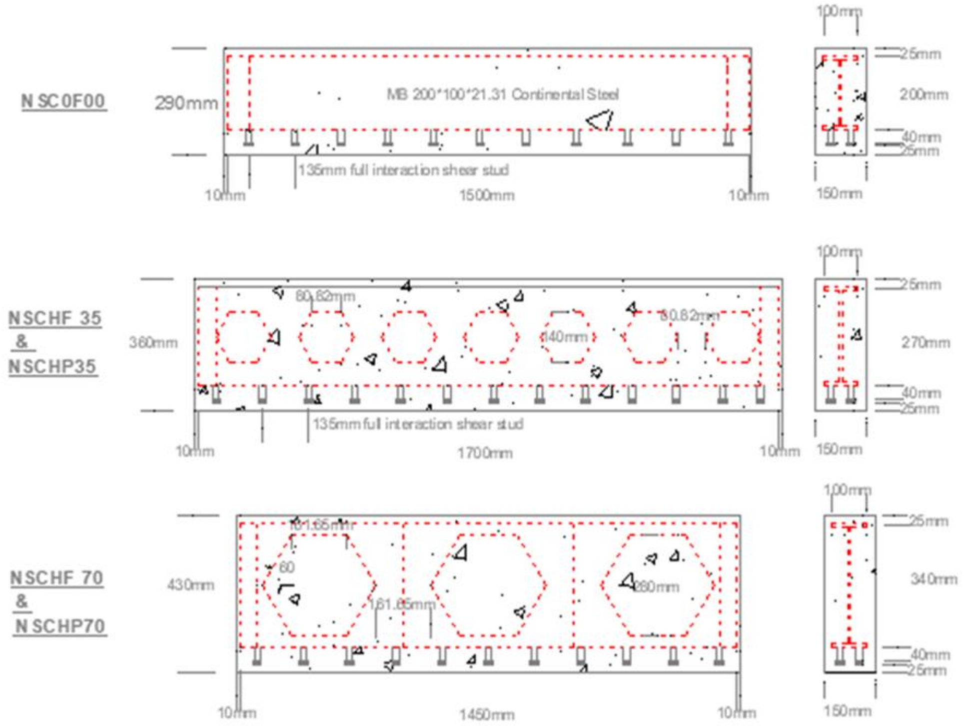


Figure 1. Cross-sectional area of castellated steel beams under general

2.3 Shear stud connectors

With an 8 mm diameter, 40 mm overall height, and 13 mm upper head diameter, a seamless shear stud connection has been adapted. The height-to-diameter ratio is 5, according to BS 5400-5 requirements [9]. The mechanical properties and requirements of the shear stud connection, as shown in Table 3.

Table 3. The geometry and mechanical characteristics of shear connections

Actual bar diameter (mm)	**Actual Head Stud diameter (mm)**	**Height of the shear connector (mm)**	**Thickness of Head Stud (mm)**	**Elastic Modulus (MPa)**	**Yield Strength fy (MPa)**	**Ultimate Strength fu (MPa)**
8	13	40	8	205000	280	400

Standardized testing has the benefit of determining the characteristics of materials in compliance with IQS and ASTM standards. This research examines ordinary Portland cement (Type I). We kept it dry to protect it from a variety of climatic situations. The results of the tests show that the chosen cement complies with Iraqi Standards (NO.5/1984) [10] as well as ASTM-C150-17 [11]. In this study, take advantage of Following the necessary evaluation, natural sand with a maximum particle size of 4.75 mm is used as a fine aggregate in the construction mix of all concrete forms. The results indicate that the graded fine aggregate satisfies the zone requirements of Iraqi standard (IQS) No.

45/1984 [12]. ASTM C128-15 [13]. The local gravel was crushed to meet Iraqi regulations, and it was utilized to make several concrete combinations with a maximum particle size of 12.5 mm. Every piece of crushed gravel is washed and kept dry for a long time before being wrapped in plastic in compliance with Iraqi Specification (IQS) No.45/1984 zone [12]. All concrete specimens used in this study were mixed and cured using clean tap water

2.5 Mixing Normal strength concrete (NSC)

The mix ratios for the normal strength concrete utilized in this investigation are listed in Table 4.

Table 4. Properties of Concrete Mix (NSC)

Combine notation	**w/c**	**Cement kg/m3**	**Water liter/m3**	**Fine Aggregate kg/m3**	**Aggregate kg/m3**
NSC	0.45	350	180	600	1200

It was sufficient to keep the mixer clean but dry before starting the NSC mixing procedure. The mixer was first loaded with gravel and sand. After that, the mixture was given a minute to become hydrated by adding a third of the mixing water. One-third of the water is added and stirred for a minute after the cement has been combined and mixed for thirty seconds. After another minute of careful stirring, the remaining water is added, for a total mixing duration of one and a half minutes. All you need to do is mix for four minutes.

3. Control specimen testing

The structural laboratory of the civil engineering department at Mustansiriyah University tested the specimens using a universal compression machine with a capacity of 3000 kn. We use an average of three specimens for all mixes. The specifications of the control specimens are shown in Table 5.

Table 5. The requirements of the control specimens

Test classification	**Quantity and classification of specimens**	**Specimen's dimension (mm)**	**average of three specimens**
Type of concrete	**NSC**		
Compression [14]	3 cubes	100×100×100	25Mpa
Modulus of rupture [15]	3 prisms	100×100×500	3.25Mpa
Splitting tensile strength [16]	3 cylinders	100×200	2.5Mpa
Modulus of Elasticity [17]	3 cylinders	150×300	26.6Gpa

4. Test results

Every specimen is tested up to failure under four point loads. Table 6 gives the first crack loads, ultimate load, Maximum deflection at mid and horizontal movement at end for each specimen.

Table 6. Ultimate load, first crack load, ultimate load, deflection at mid and horizontal displacement

Sample designation	**Initial cracking load (kN)**	**Ultimate load (kN)**	**Maximum deflection at mid (mm)**	**Maximum horizontal movement (mm)**
NSC0F00	90	390	22	4.6
NSCHF35	170	500	18	4.2
NSCHF70	140	450	22	4.34
NSCHP35	200	470	20	4.5
NSCHP70	130	440	24	6.15

4.1 Load – deflection at midspan

For each specimen, we evaluate its deflection in response to static loadings. Figure 2 displays the load-deflection curves generated for the tested specimens at each loading stage until failure. Fracture propagation caused the concrete failure, as all specimens underwent failure testing. The NSC0F00 reference specimen is made of normal-strength concrete and has a solid web with no holes in it. It interacts fully with the composite beam and has multiple stud shear connections. Matching the mid-span deflection of 22 mm, the greatest load capacity is 390 kN. The reference NSC0F00 demonstrates linear behavior between zero and 90 kN, the load associated with the initial fracture. In comparison to the NSC0F00, the specimen NSCHF35 demonstrated a mid-span deflection of 18 mm and a load capacity of 500 kN. Nevertheless, its strength was superior and its deflection inferior. On the other hand, the NSCHF70 specimen has a reduced strength capacity of 450 kN as a result of the impact of the aperture size, which enhances deflection and reduces resistance. The NSCHP35 specimen, which exhibited a mid-span deflection of 20mm, exhibited a maximal deflection of 22mm and a strength capability of 470 kN, which was greater than that of the control specimen. In comparison to NSCHP35, the specimen NSCHP70 demonstrated a reduced ultimate load capacity of 440 kN as a result of the orifice size, which increased deflection.

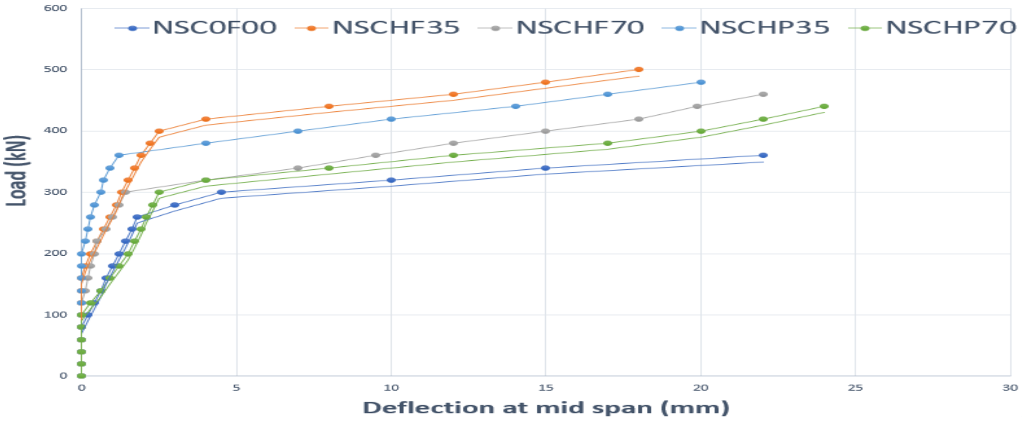


Figure 2. Load-deflection curves at mid span

4.2 Load – horizontal displacement

Even with the given number of shear stud connections, the interface surface still experiences horizontal displacement when two different materials, such as steel and concrete, act as one. Figure 3 illustrates the horizontal displacement behavior for each specimen. The horizontal displacement distribution displays a sign reversal and is symmetric around the origin (mid-span). According to complete or partial contact, the maximum horizontal movement value is 4.25–6.15 mm. The load-horizontal movement behavior at mid-span is zero, as the applied force alters the shear load's flow directions. The horizontal movement rises as the load induces greater shear flow and decreases when it is applied early. When friction is present, more dispersed shear flow leads to horizontal displacement at the interface, causing partial contact to result in more horizontal displacement than complete interaction. The frictional force's opposite direction from the shear flow increases the horizontal displacement value.

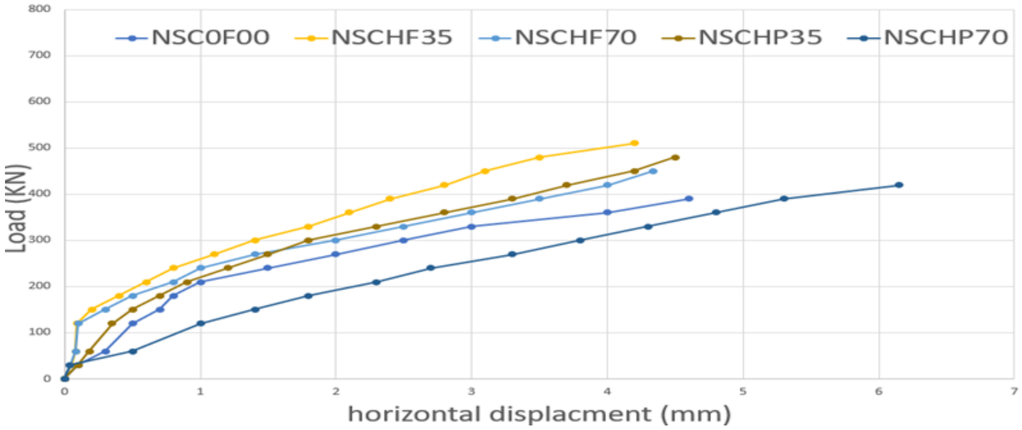


Figure 3. Load-horizontal movement for all specimens

4.3 Crack style and failure mode

Normal-strength concrete is classified as having weak tensile resistance due to its brittle characteristics. When the applied load causes tension in the tensile area that is higher than the modulus of rupture during a flexural test, cracks start to form and spread. When there is only partial contact, the initial fracture is smaller than when there is full engagement. This is because of the horizontal movement, which makes the deflection bigger and stops the concrete and steel sections from coming together, creating a burden. Collaborated to reduce the overall. The stiffness of the composite castellated beam raises the stress inside the tension zone to the point where the concrete can't hold together any longer.

Figure 4 This illustrates the failure mechanisms and fracture propagation in all composite castellated beams. During testing at the maximum loads for any specimen, there was no pull-out failure of the concrete beam and no severed headed stud shear connections. Figure 3 shows the specimen NSC0F00. At the failure stage, the fractures are mostly vertical and parallel to the beam's thickness. They start where stress is applied and go downward toward the beam's base. Each segment of the composite castellated beam bends in response to the applied stress, and concrete cracks lead to flexural failure. The specimen NSCHF35 displays a greater number of fractures at failure than NSC0F00 due to the presence of holes. The specimen NSCHF35 has a reduced number of cracks compared to NSCHF70 due to the large size of the opening. Also, the specimen NSCHF70 exhibited a decreased ultimate load. Due to the small size of the opening, the specimen NSCHP35 has a greater load capacity at failure than the NSCHP70.

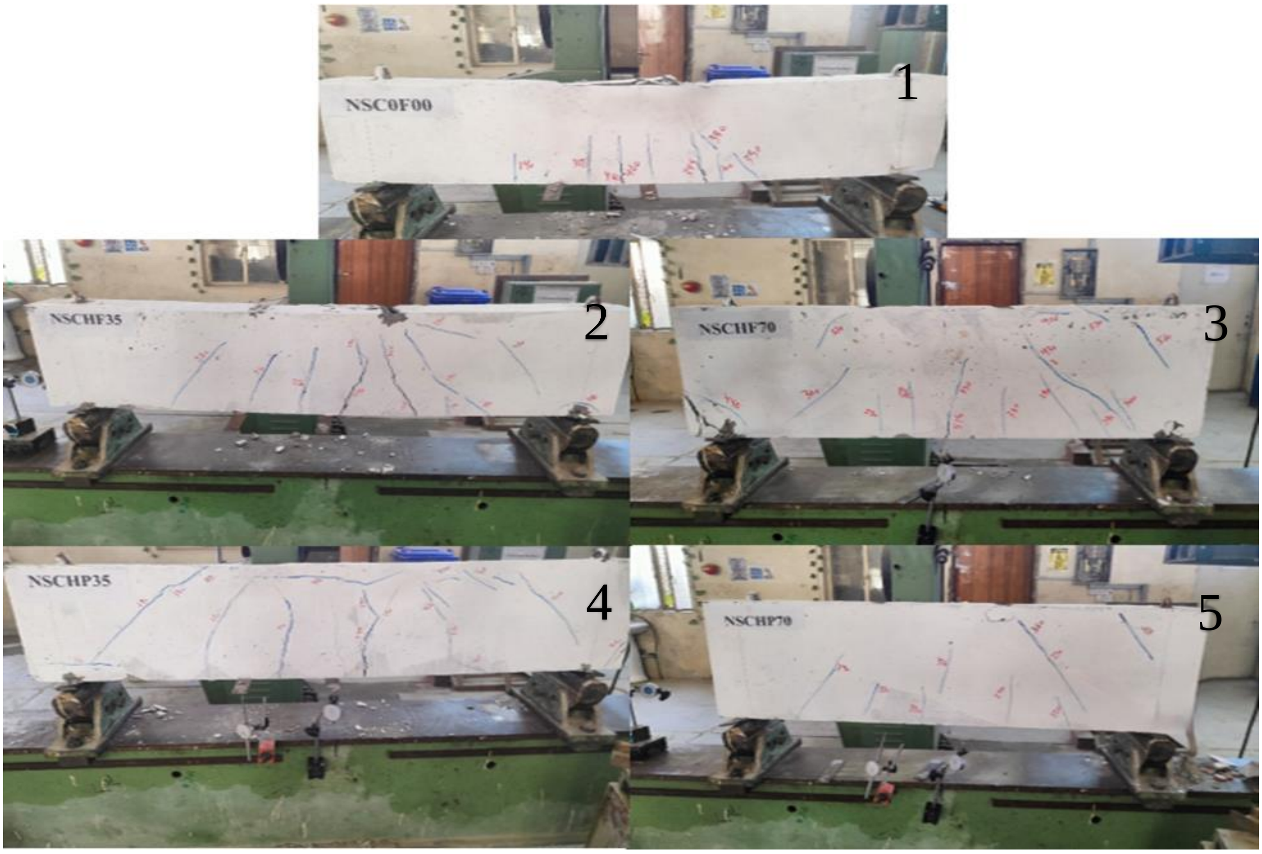


Figure 4. Composite castellated beam after failure

(1)NSC0F00,(2)NSCHF35,(3)NSCHF70,(4)NSCHP35,(5)NSCHP70

5. Discussions

The experiments performed with various parameters in this research have yielded the following observations, based on test results and findings. Table 7 illustrates a comparison of the specimens according to their opening dimensions (140mm and 280mm). Substantial voids undermine load-bearing capacity, increase deflection, and raise horizontal displacement.

Table 7: Composite castellated beams: Impact of opening size on ultimate load, deflection, and horizontal movement

the specimen	**Ultimate load (kN)**	**% Increases in ultimate load**	**Midpoint deflection maximum (mm)**	**% Decrease in deflection**	**Maximum horizontal displacement (mm)**	**% Decrease in horizontal displacement**
NSCHF35	500	11.12	18	18.2	4.2	3.22
NSCHF70	450	-------	22	-------	4.34	-------

Partial and complete interaction theories are used to assess mid-span deflection and horizontal displacement in the construction of composite castellated beams. Table 8 illustrates the horizontal displacement of composite castellated beams. The system functions as a cohesive entity when there is total contact between the concrete and the castellated steel beam. An increased number of shear stud connections leads to complete interaction, which reduces horizontal displacement and deflection, hence enhancing the capacity of the composite beam relative to a partial system by minimizing shear flow transfer between the surfaces in contact with the shear connectors.

Table 8. Composite castellated beams: Influence of stud connection on ultimate load, deflection, and lateral movement.

the specimen	Ultimate load (kN)	% Increases in ultimate load	Midpoint deflection maximum (mm))	% Decrease in deflection	Maximum horizontal displacement (mm)	% Decrease in horizontal displacement
NSCHF35	500	6.38	18	10	4.2	6.67
NSCHP35	470	-------	20	-------	4.5	-------
NSCHF70	450	2.3	22	8.34	4.34	29.4
NSCHP70	440	-------	24	-------	6.15	-------

6. Conclusions

The dimensions of the aperture and the shear stud are the two primary parameters affecting the division's sectional characteristics. The experimental analysis of the concrete beam around the castellated steel section yielded the following results:

1-The hexagonal opening sample of opening size 280 mm restricts the load-bearing capability of composite castellated beams compared to the hexagonal opening sample of opening size 140 mm due to the great depth opening.

2-The test results show that the hexagonal opening sample with a dimension of 140 mm enhances load-bearing capacity, reduces deflection, and minimizes horizontal displacement. The percentages of load-bearing capacity increase by about 11.12%. In comparison to the sample with a hexagonal opening size of 280 mm, the midpoint displacement decreased by about 18.2%. Additionally, reduce horizontal displacement by about 3.22%.

3-The interaction between the concrete and the shear stud at the foot of the steel castellated beam produced a cohesive structure. An increase in the quantity of shear stud connectors results in less shear flow transmission across the contact surfaces of the shear connections. A comprehensive contact yields an increased ultimate load. For the sample with the same aperture, the load-bearing capacity enhances by around 6.38% when using an NSCHF35 in comparison to an NSCHP35, accompanied by reductions in deflection and horizontal displacement percentages of roughly 10% and 6.67%, respectively. For the sampled NSCHF70, the load-bearing capacity rises by about 2.3% relative to the sample NSCHP70. Samples with complete contact demonstrate a decrease in halfway deflection and horizontal displacement percentages of around 8.34% and 29.4%, respectively.

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