Dijlah Journal of Engineering Science (DJES) Vol. 2, No. 3, Aug., 2025, pp. 41- 51

ISSN: Printed: **3078-9656, Online: 3078-9664**, paper ID: 51

Flexural Behavior of Hollow Composite Beams with Different Voids Ratio Under Monotonic Load

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Article Info

Article history:

Received 12, July, 2025
Revised 10, July, 2025
Accepted 12, July, 2025

Keywords:

Experimental work
Flexural behavior
Hollow Composite Beams,
Shear Connectors
Steel Channel Anchors.

ABSTRACT

This research aims to study the flexural behavior of hollow composite beams with simple supports, consisting of a concrete slab connected to an I-beam steel beam, held together by shear connectors. The experimental work involved casting eight specimens, divided into four groups based on void ratio used: 9%, 18%, and 27%. Shear connectors in the form of steel studs were used in different numbers. Composite beams were tested under monotonic loading, using two void-free composite beams as reference specimens. The results showed that the use of voids reduced the ultimate load to failure of the beams by 8.4, 19.7, and 34.9%, respectively. The use of 13 pairs of steel nails instead of 6 pairs in the hollow composite beams increased the ultimate load by 2.7%. The failure mode for all specimens was flexural failure.

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1. INTRODUCTION

Composite metal-concrete beams utilizing solid-in-region concrete slabs, whether or not strong or hole, exhibit numerous drawbacks, which includes the increased operating fees related to welding shear connections and the prolonged drying time of wet concrete in cold areas. To alleviate those drawbacks, precast hollow center concrete slabs (PCICS) can also function a feasible opportunity. These additives are manufactured in regulated situations, making use of a unique operation and stringent technological oversight. The utilization of PCICS slabs affords benefits like large coverage, speedy installation, and reduced building costs [1]. During fantastic bending of the composite beam, the strengths of the special additives are used most successfully. In this situation, the concrete slab usually endures compressive forces, at the same time as the metallic beam studies tensile stresses, consequently leveraging the useful traits of every fabric [2]. Due to the necessity of covering extensive distances with increased loads, significant research has been conducted on deep hollow slabs. Notwithstanding the limitations of the SCI P401 publication, as stipulated by Eurocode 4, which pertains exclusively to hollow core slabs with depths ranging from 150 to 250 mm, with or without a concrete layer, researchers investigated hollow core slabs incorporating a concrete layer to assess their impact on the flexural behavior of composite beams composed of steel and concrete, recognizing that the hollow core depth exceeds the parameters set forth in the SCI P401 guidelines. Subsequently, hollow core units with diameters of 150 mm and 265 mm, in conjunction with a concrete layer, were examined to ascertain the increase in depth. A comprehensive analysis of the computational parameters was conducted by modifying the concrete strength, transverse reinforcement ratio, shear connection spacing, and steel cross-section. Both complete and partial response models have been analyzed, indicating that under certain situations, identical resistances may be achieved, implying that comparable power output may be produced with fewer shear studs, hence reducing power consumption [3]. Lam documented flexural studies on steel-concrete composite beams. A four-point bending test was evaluated. The concrete layer was not taken into account. Experimental results indicated rapid failure due to shear connector rupture and concrete cracking, resulting in reduced stiffness [4]. Unlike well-known composite beams, Zhang et al. (2022) proposed a prefabricated composite beam, consisting of two full-size precast concrete (FDPC) slabs, providing rapid assembly and construction [5]. The primary role of shear connectors is to resist the lateral movement of composite section beams and transmit horizontal shear forces across the interface between the concrete slab and the steel section. These connectors also prevent the concrete slab from separating vertically from the steel section, thus maintaining the integrity of the structure [6]. Numerous styles of shear connections exist, with head studs being the most important shear connector in composite beams, attributable to their traits. A bendy connector nearing its maximum energy persists in deforming without fracturing, permitting neighboring shear connectors to house the heightened shear. The elastic properties of those connections, allowing relative movement between the concrete slab and the steel phase prior to reaching most pressure, make contributions notably to their time-honored software in composite beams. The resistance to shear strain and stiffness of the metallic-concrete connection is contingent no longer handiest upon the electricity of the shear connector but additionally at the concrete slab's capability to withstand cracking due to the massive awareness of shear stresses at every connector [7]. Recent research into shear joints has focused on improving design and performance using advanced materials and manufacturing methods. High-strength bolts have been used to enhance shear transfer capacity, while advances in welding techniques have enabled shear joints to be manufactured more accurately and quickly. Research has also expanded the horizons of composite beam construction through the development of new materials, such as advanced steel alloys and high-performance concrete [8].

2. MATERIALS

2.1. Materials and specimen description

-Cement: The cement used in casting all composite beam specimens was ordinary Portland cement (Type I). Which complies with IQS No. 5/1984 [9].

- The fine aggregate used in all experiments was natural sand sourced from Iraqi rivers, meeting the requirements of Iraqi Quality Specification No. 45/1984 [10].

-Coarse aggregate: Natural gravel extracted from Iraqi rivers, with a maximum size of 12.5 mm, was used as coarse aggregate in the experimental work, meeting the specifications outlined in IQS No. 45/1984.

-Steel bars: deformed steel bars with a diameter of 6 mm are used for composite beams were constructed.

- steel I-section, designated IPE_140 is used

-Water: potable water was used to treat and mix all specimens.

- Shear connectors of the steel stud anchor type, measuring 10 mm in diameter and 50 mm in length, were utilized.

- Cork pieces with a density of 7 kg/m³ were utilized to form voids in the concrete slabs. The lowest cork density available was chosen because increasing the cork density could lead to an increase in the weight and stiffness of the composite beams and thus could affect the flexural behaviour of these beams.

The properties of the steel used are shown in Table 1. These bars comply with the specifications set forth in ASTM A 615 [11] and AISC 18.2d [12].

Table 1. Physical properties of steels.

Item	Specimen No.	Actual dim. (mm)	Yield strength (N/mm2)		Ultimate Strength(N/mm2)	
I-section	1	140 x73	359	350	481	476
	2		339		469	
	3		352		478	
Deformed Steel bars	1	6 diameters	388	392	555	543
	2		391		543	
	3		397		531	
Stud anchors	1	.	643	655	765	773
	2	10 diameters	667		783	
	3		655		771	

2.2. Concrete mix design

Table 2 Displays the weight-based mixture proportions utilised in experimental work as per ACI 211.1-91 [13].

Table 2. Mix proportion

Materials	W/C	Water	Cement	Fine. A	Coarse. A
Quantity (kg/m^3)	0.418	155	370	830	1045

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2.3. Concrete's mechanical properties

The compressive strength (f'c) of concrete was assessed per ASTM C39-14, resulting in 32 MPa. The flexural strength (f_r) and splitting tensile strength (f^t) were determined to be 3.2 MPa and 4.22 MPa, respectively, in accordance with ASTM (2010) and ASTM C496M-04.

3. COMPOSITE BEAMS DETAILS

The beam is 1250 mm long (center to center). The concrete slab dimensions are 320 mm wide and 85 mm deep. The effective width was determined according to AISC LRFD standards, and the The concrete slab was designed and reinforced according to ACI building code specifications, using 6 mm diameter reinforcing bars at the mid-depth of the concrete slab cross-section, while maintaining a suitable concrete cover to ensure the reinforcement is protected from environmental influences

. The bars were spaced 100 mm center to center in each direction. Figure 1 shows the details of the specimens. The IPE-140 steel I-section was 140 mm deep, with 6 mm thick flanges and a width of 73 mm.

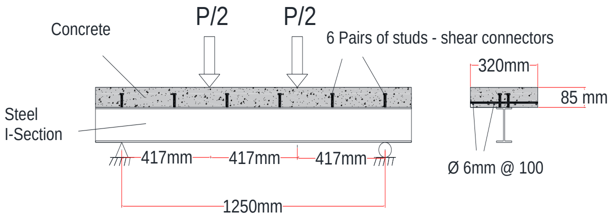
3.1 Calculations of voids ratio

Total slab volume = 320mm * 85mm *1500mm = $408*10^5$
First volume of voids = 30mm * 40mm *1500mm * 2 = 36 $*10^5$ mm^3
Second volume of voids = 30mm * 40mm *1500mm* 4 = 72 $*10^5$ mm^3
Third volume of voids = 30mm * 40mm *1500mm * 6 = 108 $*10^5$ mm^3

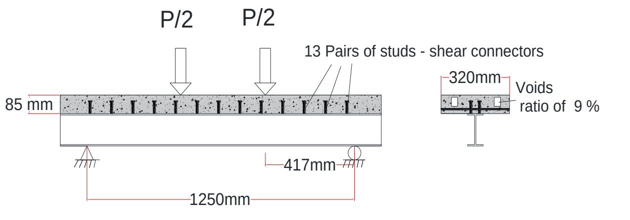
Voids ratio = volume of voids/ total slab volume
First void ratio = (36 *105/408$*10^5$) *100% = 9 %
Second void ratio = (72 *105/408$*10^5$) *100% = 18%
Third void ratio = (108 *105/408$*10^5$) *100% = 27%

3.2. Nomenclatures

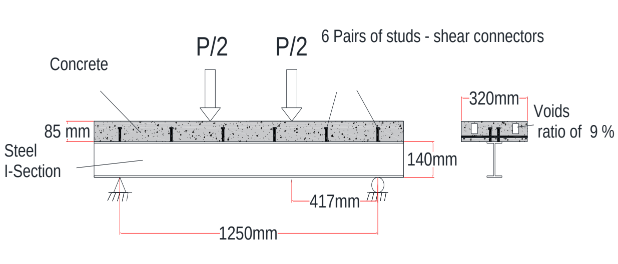
C : composite beam
S1: The first group of studs
M: monotonic load
9,18,27: voids ratios respectively
S2 : The second group of studs



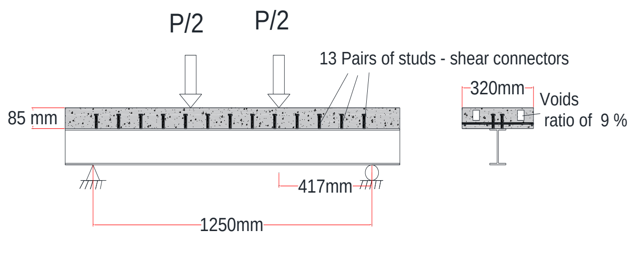
a) CS1



b) CS2



c) C9S1M



d) C9S2M

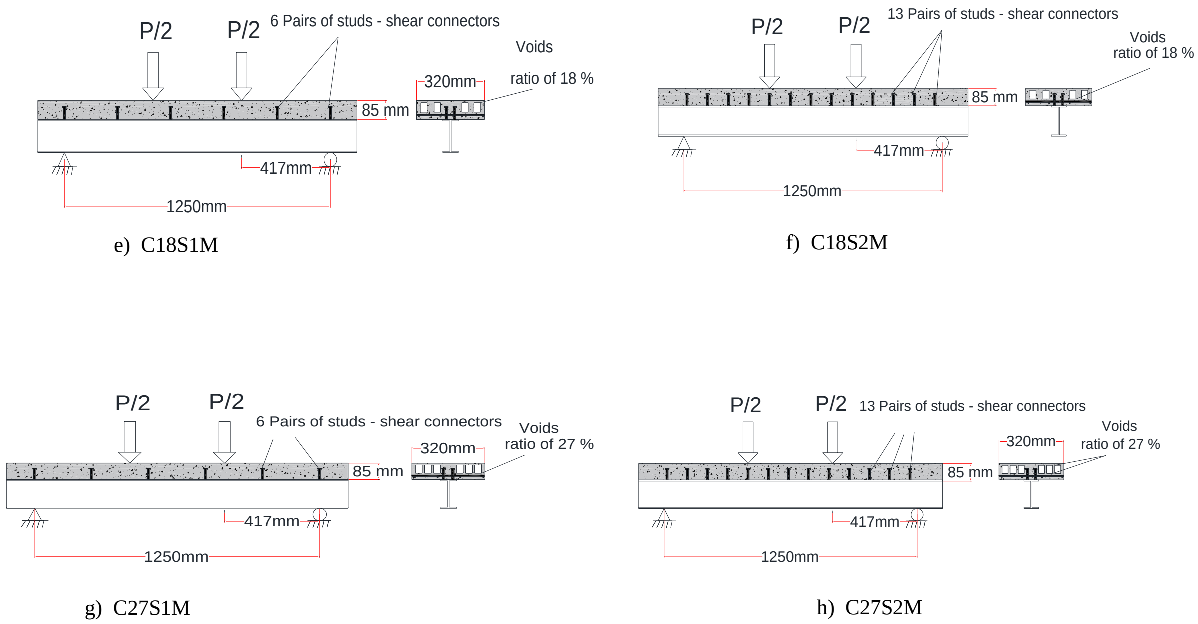


Figure 1. Details Of Hollow Composite Specimens

4. Experimental Program

The experimental program consisted of casting 8 composite steel-concrete beams, categorized based on void ratios and shear connector numbers. Three void ratios were proposed: 9%, 18%, and 27% in addition to 0% voids ratio for control specimens. The beams were cast with precise placement of pieces cork to achieve the desired void ratios. A single type of shear connector was used: headed studs with two numbers (6 and 13 pairs). The specimens were classified into four groups, and the casting procedure was carried out according to the specified details for each group.

The casting procedure involved fabricating four groups of composite beams with distinct characteristics:

1. Group A1 (Control Specimens with 0% Void Ratio): Two solid composite beams were cast, each containing a different number of steel stud anchors (6 and 13 pairs, respectively).

2. Group A2 (9% Void Ratio): Two composite beams were cast with a 9% void ratio, each featuring a different number of steel stud anchors (6 and 13 pairs, respectively).

3. Group A3 (18% Void Ratio): Two composite beams were cast with an 18% void ratio, each containing a different number of steel stud anchors (6 and 13 pairs, respectively).

4. Group A4 (27% Void Ratio): Two composite beams were cast with a 27% void ratio, each featuring a different number of steel stud anchors (6 and 13 pairs, respectively).

Table 3. Design configurations of the composite Beams

Beam Group	Designation	Voids Ratio (%)	Shear Connector Types	Number. of Shear Connectors
A1	CS1	0	steel stud	6 pairs
	CS2	0	steel stud	13 pairs
A2	C9S1M	9	steel stud	6 pairs
	C18S2R	9	steel stud	13 pairs
A3	C18S1M	18	steel stud	6 pairs

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	C18S2R	18	steel stud	13 pairs
A4	C27S1R	27	steel stud	6 pairs
	C27S2R	27	steel stud	13 pairs

4.1 Testing procedure

4.1.1. Loding of specimens

Composite beams were tested in the graduate laboratory of the College of Engineering at Tikrit University using a hydraulic bending machine with a force of 300 kN and a rotation speed of 2 kN/s. The hydraulic jack used a four-point load, where the forces were distributed equally at two points at one-third of the beam span (see Figure (2)). A monotonic loading consisting of one increasing cycle until failure was used. The void-free specimens were considered reference specimens for the other specimens with three void ratios.

Figure 2. Testing setup

4.1.2 Deflection Measurement

Vertical deflection values were obtained using linear variable differential transformers (LVDTs) placed below the composite beam specimen, in contact with the center of the bottom surface of the concrete.

5. RESULTS AND DISCUSSION

5.1. Load-deflection relationship

In general, it was observed that the monotonic loading leads to a gradual increase in deflection until failure occurs. Figure (3) illustrates the relationship between load and deflection for all composite beams tested under monotonic loads throughout all loading stages until failure. It was found that these relationships are highly dependent on the void ratio and the number of shear connectors used.

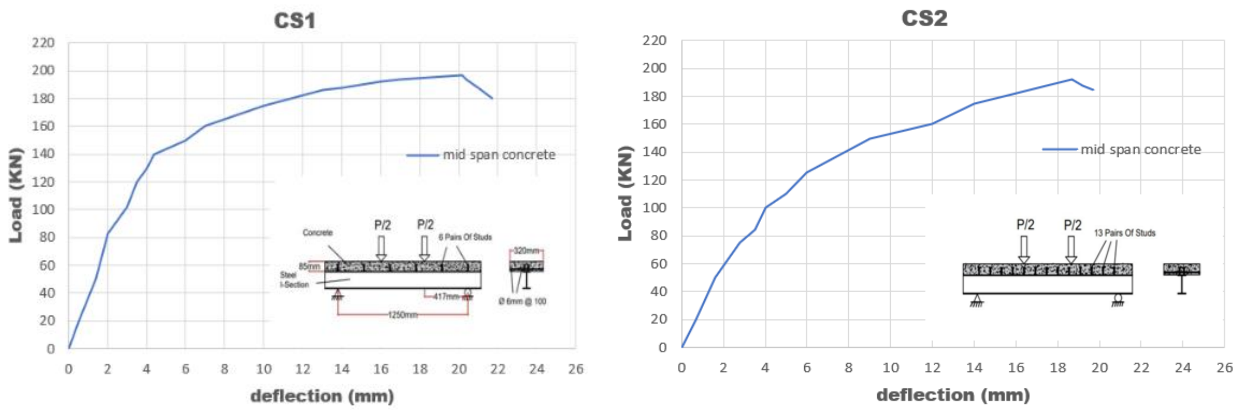

Figure 3. Load – deflection relationship for specimens with voids (0 %)

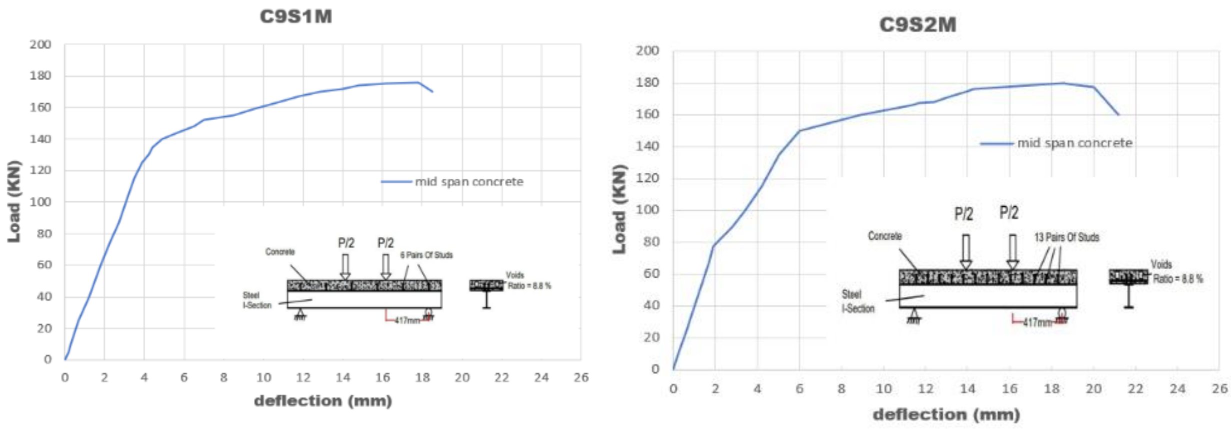

Figure 4. Load-deflection relationship for specimens containing voids (9%)

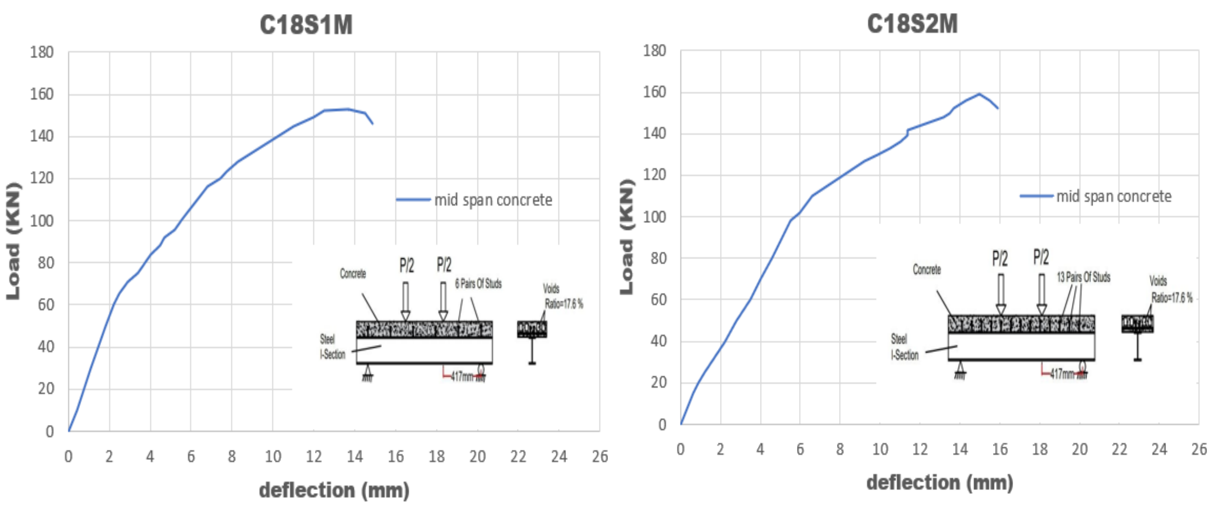

Figure 5. Load-deflection relationship for specimens containing voids (18%)

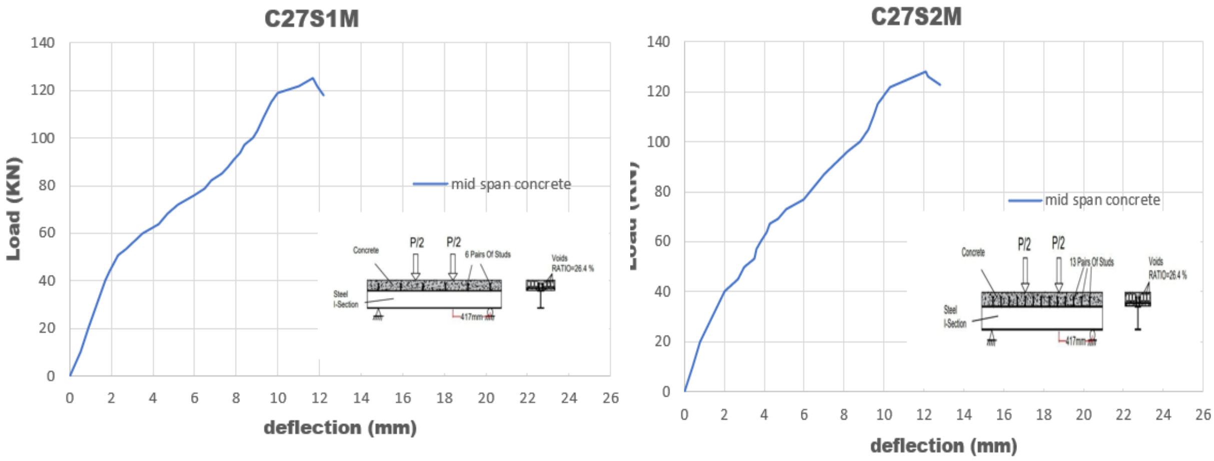

Figure 6. Load-deflection relationship for specimens containing voids (27%)

5.2. Load-deflection response of composite beams

In the initial group (A1) of solid specimens, it is evident that the maximum deflection of the composite beam (CS1) under monotonic loading increased by roughly 7.4% relative to the comparable specimen (CS2). In the second group (A2) of specimens with 9% voids, the maximum deflection of the composite beam (C9S1M) under monotonic loading reduced by approximately 4.3% compared to the equivalent specimen (C9S2M). In the third group (A3) of specimens with 18% voids, the maximum deflection of the composite beam (C18S1M) under monotonic loading reduced by approximately 8.6% compared to the equivalent specimen (C18S2M). In the fourth group (A4) of specimens with 27% voids, the maximum deflection of the composite beam (C27S1M) under monotonic loading diminished by about 3.3% in comparison to the equivalent specimen (C27S2M). Augmenting the quantity of shear connections turned into visible to diminish deflection in void-crammed specimens. This is because of the improved shear resistance between the concrete slab and the metallic phase, which elevates the ultimate load at the beam and therefore diminishes deflection. In void-unfastened beams, augmenting the quantity of shear connections may additionally set off sensitivity to deformation or modify the pressure distribution inside the beam, culminating in a reduced closing load and heightened deflection, notwithstanding more suitable beam overall performance. Refer to Table 4

5.3. Effect of changing voids ratio

In the second set (A2) of specimens with a 9% void ratio, the maximum loads of the composite beams (C9S1M) and (C9S2M) diminished by 36.5% and 33.3%, respectively, yielding an overall reduction rate of 34.9% in comparison to the void-free specimens (0% void ratio). In the third group (A3) with an 18% void ratio, the maximum loads of the composite beams (C18S1M) and (C18S2M) diminished by 22.3% and 17.1%, respectively, yielding a 19.7% reduction compared to the void-free specimens (0% void ratio). In the fourth group (A4) with a 27% void ratio, the maximum loads of the composite beams (C27S1M) and (C27S2M) diminished by 10.6% and 6.2%, respectively, leading to an overall reduction rate of 8.4% compared to the void-free specimens (0% void ratio). The reduction in maximum load with a higher vacancy ratio may result from heightened stress on the residual material, as the identical load is allocated across a diminished area, hence elevating the likelihood of failure.

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ISSN: Printed: **3078-9656, Online: 3078-9664**, paper ID: 51

Table 4. Results of tested composite beam specimens.

Beam Group	Designation	Voids Ratio (%)	Shear Connector Types	Nu. of Shear Connectors	Initial cracking load (kN)	Max. load (kN)	Max. Def. (mm)
A1	CS1	0	studs	6 pairs	87	197	20.2
	CS2	0	studs	13 pairs	84	192	18.7
A2	C9S1M	9	studs	6 pairs	87	176	17.8
	C9S2M	9	studs	13 pairs	77	180	18.6
A3	C18S1M	18	studs	6 pairs	71	153	13.7
	C18S2M	18	studs	13 pairs	98	159	15
A4	C27S1M	27	studs	6 pairs	50	125	11.7
	C27S2M	27	studs	13 pairs	44	128	12.1

5.4. Effect of changing the number of studs

In the primary group (A1) of void-unfastened specimens, the most load of the composite beam (CS1) decreased by using approximately 2.5% compared to the corresponding specimen (CS2). In the businesses containing voids ratio (A2, A3, and A4), an increase in the maximum load of the composite beams was observed as follows:
For the second group (A2) of specimens containing 9% voids, the maximum load of the composite beam (C9S1M) increased by approximately 2.2% compared to the corresponding specimen (C9S2M).
For the third group (A3) of specimens containing 18% voids, the maximum load of the composite beam (C18S1M) increased by approximately 3.7% compared to the corresponding specimen (C18S2M).
For the fourth group (A4) of specimens containing 27% voids, the maximum load of the composite beam (C27S1M) increased by approximately 2.3% compared to the corresponding specimen (C27S2M).

These results indicate that increasing the number of shear connectors leads to an increase in the ultimate load of specimens with voids, which may be due to the increased shear strength and increased bonding between the steel section and the concrete slab, thus increasing the resistance of the beam to failure. However, for void-free beams, increasing the number of shear connectors can lead to changes in the stress distribution within the beam or changes in failure behavior, thus reducing the ultimate load of the beam and then failure.

5.5. Failure modes

The tested composite beams mainly showed flexural failure, characterized by initial cracking in the tensile zone of the concrete followed by propagation of diagonal and longitudinal cracks with increasing load. Figure (6) shows the failure mode of the tested specimens.

a) CS1

b) CS2

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e) C18S1M

f) C18S2M

g) C27S2M

h) C27S2R

Figure 7. Failure mode for some testing specimens

Cracks begin to appear at the bottom of the concrete slab in the tension zone under the influence of four-point loading. With increasing load, these cracks widen and become deeper. With increasing load, the diffraction axis shifts upward toward the compression zone, leading to specimen failure. In addition to diagonal cracks, longitudinal cracks appeared in some specimens. These longitudinal cracks may be due to weak longitudinal reinforcement. The length of the shear connectors welded to the steel section also affects this type of failure. Longitudinal cracks appeared in two specimens (C18S2M and C27S2M). as shown in Figure (7).

Figure 8. Longitudinal pattern specimens

6. CONCLUSIONS

According to this study, a number of results were extracted, which were as follows:

1. The results showed that increasing the void ratio resulted in lower ultimate failure loads resulting from the uneven stress distribution within the beam. The ultimate load reduction was (8.4%, 19.7%, and 34.9%) for void ratios of (9%, 18%, and 27%), respectively, compared to void-free specimens. These results highlight the importance of selecting the optimal void ratio in the design of hollow composite beams.

2. Voids in hollow composite beams have varying impacts on both cost and implementation. On the cost side, voids reduce material usage, resulting in cost savings. On the other hand, voids contribute to implementation complexity. Accurate void distribution is critical, as voids in high-stress zones increase the risk of failure.

3. The results showed that using 13 pairs of shear connections instead of 6 pairs in the hollow composite beam specimens increased the maximum load by 2.7%. This increase in maximum load is attributed to the ability of the shear connections to distribute loads more efficiently and increase the bond strength between the steel section and the concrete slab, resulting in improved load-bearing capacity of the hollow composite beams.

4. No lateral sliding occurred in any of the composite beam specimens tested.

5. It is not possible to determine the best void ratio for specimens because this depends on the influencing factors that include weight, strength, thermal insulation and economic cost. The higher the void ratio, the lower the weight of the concrete and thus the lower the strength of the concrete, the lower the economic cost and the greater the thermal insulation.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the Head and staff of the Department of Civil Engineering, College of Engineering, Tikrit University, for providing generous financial support for this research.

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ISSN: Printed: **3078-9656, Online: 3078-9664**, paper ID: 51

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