Dijlah Journal of Engineering Science (DJES) Vol. 3, No.1, March, 2026, pp.79-87
ISSN: Printed: **3078-9656, Online: 3078-9664**, paper ID: 112

Influence of Openings and U-section Height Variation on the Structural Behavior of Steel-concrete Composite Beams Containing Openings

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Article Info

Article history:

Received Oct.,14, 2025
Revised Dec., 20, 2025
Accepted Feb. 25, 2026

Keywords:

Composite Beams
U-shaped steel section
Cold-formed steel section
Service openings
Shear connecter

ABSTRACT

This study investigates the experimental effect of openings and varying steel section heights on the structural behavior of concrete-filled cold-formed U-shaped composite beams. Four specimens were fabricated and tested under four-point loading: one reference beam without openings (CB1) and three with circular openings at different section heights (300, 350, and 400 mm). The results showed a 16% reduction in the ultimate flexural strength with openings compared to the reference beam, with a significant increase in deflection and slippage due to the loss of effective section area and the formation of stress concentrations around the openings. Increasing section height, on the other hand, gradually improved strength and stiffness, with the ultimate load reaching 305 kN at a height of 400 mm, indicating the ability of the larger section to redistribute stresses and reduce slippage. The specimens also demonstrated a transition in failure mode from localized failure around the openings to a more uniform flexural failure at higher heights. These results emphasize the importance of incorporating geometric considerations of openings and height into the design to ensure efficient performance and safety of modern composite beams.

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1. INTRODUCTION

Cold-formed steel composite section filled with concrete (CUCB) is a modern structural system characterized by its lightweight and efficient performance, making it a promising option for advanced engineering applications. Its most prominent advantages are the following:(1) The concrete encased within the steel section supports the thin walls and delays or prevents localized buckling of the steel [1, 2], unlike the open H-shaped steel sections used in conventional composite beams (HCB), which require a strict definition of the aspect ratio to avoid buckling;(2) The integrated interaction between the encased concrete and the outer steel section contributes to increased shear strength and reduces the likelihood of brittle failure [3-7]; (3) The presence of concrete containing a percentage of moisture [8] also helps absorb the heat generated by steel during fires, slowing its temperature rise. Meanwhile, the longitudinal reinforcing bars within the concrete act as a second line of defense when the outer steel plates lose their capacity at high temperatures. Despite this type of section's limited prevalence, its details and design forms exhibit remarkable diversity [9]. Figure (1) displays a variety of U-shaped steel section models.

Openings in structural elements, especially in beams, are a basic requirement in modern buildings, as they allow mechanical, electrical, and plumbing systems to pass through the section without the need for substantial modifications to the distribution of structural elements. When services integrate within beams instead of passing beneath them, they improve space utilization efficiency and reduce floor heights. Architecturally designed openings can also contribute to reducing the self-weight of wide or deep elements, thus reducing the loads transferred to the foundations. However, introducing openings requires careful structural study due to the local weakness in moment and shear strength and the generation of stress concentrations around the openings.

This research focuses on an analytical and experimental study of the effect of service openings on the structural behavior of composite beams composed of concrete-filled cold-formed steel U-shaped sections equipped with channel-type shear connectors. The study aims to analyze failure modes, determine the maximum beam load, and measure both deflection and sliding at the steel-concrete interface, enabling a more accurate understanding of performance mechanisms and factors affecting structural efficiency. It also compares the behavior of composite beams with and without service openings and examines the effect of different U-shaped section heights on the overall behavior of these beams when openings are present. Despite the diversity of previous studies on traditional composite beams, research addressing the impact of service openings on composite beams made of cold-formed steel sections remains limited. This highlights the importance of this study in bridging this research gap and providing a scientific basis for future design development of this type of composite system.

(a) Profiled sheets (b) Valgus top flanges (c) Varus top flanges (d) Welded light steel

Figure 1. Various kinds of steel U-sections [9].

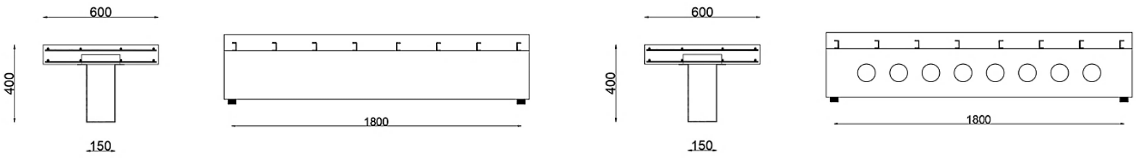
2. Experimental program

2.1. Specimen design

Four simple support composite T-beams were prepared with the following geometric properties: bottom width 150 mm, upper flange width 50 mm, concrete slab thickness 100 mm, reinforcement protection cover 20 mm, total member length 1900 mm with effective span 1800 mm, and integral concrete slab width 600 mm. The beam depth (H) varied between the specimens as shown in Table 1, to study the effect of depth variation on structural behavior. Figure 2 shows the structural details of these specimens.

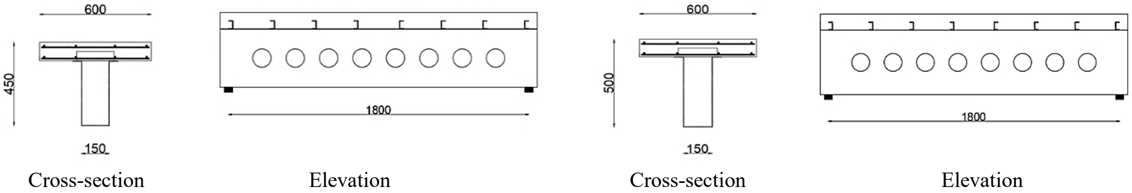
Table 1. Parameters of the composite beam specimens (unit: mm).

Specimens Symbol	Length	Depth of U-Section	Thickness of U-Section	Concrete Slab width	Concrete Slab thickness	Width of the lower part	Spacing between channel connecter	Shape of opening
CB1	1900	300	3	600	100	150	250	No opening
CB2	1900	300	3	600	100	150	250	Circular
CB3	1900	350	3	600	100	150	250	Circular
CB4	1900	400	3	600	100	150	250	Circular



Cross-section Elevation Cross-section Elevation

(a) Specimen CB1 (b) Specimen CB2



(c) Specimen CB3 (d) Specimen CB4

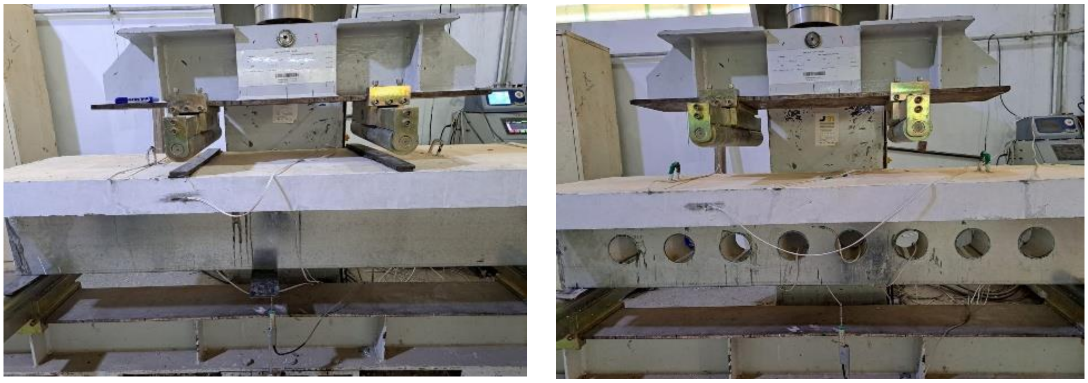
Figure 2. Details of specimens (unit: mm).

2.2. Specimen fabrication

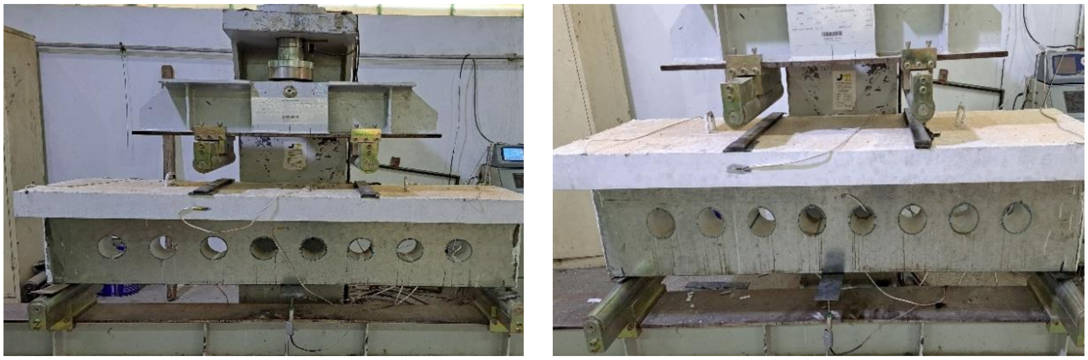
All specimens were manufactured from 1900 mm long cold-formed U-shaped steel sections at a local factory and then poured with reinforced concrete. To achieve composite bonding, a double shear connector system was used. Welded bolts, 10 mm in diameter and 85 mm high, were placed along the longitudinal axis of the section base at 150 mm intervals. Steel channel sections (C-50×25×3 mm), 200 mm long, were welded to the upper flanges at 250 mm intervals. The concrete slabs were reinforced with two layers of 10 mm diameter bars, 200 mm apart in the longitudinal and transverse directions, with a 20 mm thick concrete cover to protect against corrosion and environmental factors. Variations between specimens were limited to the presence of openings and section height. The reference specimen CB1 was designed without openings at a height of 300 mm, while specimens CB2–CB4 contained eight circular openings with a diameter of 110 mm distributed along the neutral axis of the beam, with the first opening located 250 mm from the edge and repeated at a center-to-center distance of 200 mm. The height was 300 mm in CB2, 350 mm in CB3, and 400 mm in CB4 to evaluate the effect of increased height on the structural behavior of the beams with openings compared to the reference specimen. Figures 3 and 4 shows the specimens and the construction procedure.


(a) channel connectors welded to the top flanges
(b) Slab reinforcement

Figure 3. The construction procedure of specimens.



(a) Specimen CB1 (b) Specimen CB2



(c) Specimen CB3 (d) Specimen CB4

Figure 4. Composite beams.

2.3. Material properties

The mechanical properties of the structural materials used in this study were determined based on relevant American standard specifications to ensure the accuracy of the results and their conformity with international standards. Tensile tests of steel sheets, steel channels, and bolts were conducted according to ASTM E8/E8M [10] and ASTM A370 [11], while reinforcing bars were tested according to ASTM A615/A615M [12] that is used in concrete reinforcement. Concrete tests included testing six concrete cylinders with a diameter of 150 mm and a height of 300 mm and three prisms with dimensions of 100 x 100 x 500 mm, according to ASTM C39/C39M [13] specifications to determine compressive strength, ASTM C78/C78M [14] specifications to determine flexural strength, ASTM C496/C496M [15] specifications to evaluate splitting tensile strength of concrete. The measured material properties are given in Table 2 and Table 3.

Table 2. Measured material properties.

Material	Diameter/thickness (mm)	Yield strength (MPa)	Ultimate strength (MPa)
Reinforcement	Ø10	640	744
Steel Sheet	3	344	439
Channel	3	316	400
Bolt	10	225	665

Table 3. Hardened concrete properties of the specimens.

f'_c MPa, 28 days cylinders	f_{ct} MPa, 28 days cylinders	f_r MPa, 28 days prisms	E_c MPa Modulus of elasticity
25	3.51	6.27	23500

2.4. Test model and measuring scheme

Four-point bending tests were performed on the specimens, where each specimen was placed on simple supports at both ends, and two equal point loads were applied at two-thirds of the span, as shown in Figure 5, with the aim of generating a constant moment region at the mid-span. The loading process was carried out with a gradual increase according to a force control protocol to ensure accurate response monitoring. LVDT devices were used to measure the deflection at the mid-span, in addition to measuring the relative slip at the end of the beam.

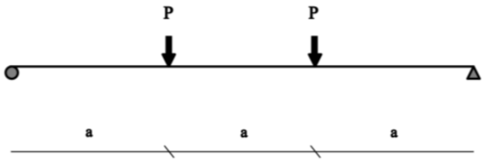


Figure 5. Force distribution on composite beams.

3. RESULTS AND DISCUSSION

To illustrate the quantitative differences between the tested models, Table 4 shows the basic values for maximum load, deflection, and interstitial slip. This presentation aims to highlight the effect of the presence of openings and increased section height on the overall performance of the composite beams and to evaluate the extent of improvement or deterioration in the structural behavior of each model.

Table 4. Results for all specimens.

Beam Symbol	Ultimate Load (kN)	Deflection(mm)	Slip(mm)
CB1	340	4.643	0.628
CB2	285	7.260	1.428
CB3	290	6.892	1.392
CB4	305	6.387	0.946

3.1. Ultimate Load Capacity

The test results showed that the inclusion of openings in the cold-formed U-shaped steel section resulted in a significant decrease in the ultimate load capacity of the composite beams compared to the reference model. Figure 6 showes that model CB1 the reference beam with a height of 300 mm and no openings, recorded the highest ultimate load of 340 kN, with balanced flexural behavior indicating effective interaction between the concrete confined within the steel section and the shear connectors.Model CB2 which contained circular openings of a similar height (300 mm), showed a decrease in ultimate strength to 285 kN, approximately 16% compared to the reference model. This decrease is attributed to the loss of a portion of the effective section in the region of maximum moment and to the redistribution of stresses around the perimeter of the openings, leading to increased stress concentration and reduced local flexural and shear resistance.In CB3, whose height was increased to 350 mm while retaining the openings, the maximum capacity improved slightly to 290 kN. This relative improvement indicates that the increased height contributes to increased moment resistance, but it is not sufficient to compensate for the loss caused by the presence of the openings. Meanwhile, CB4, with a height of 400 mm, achieved a more pronounced performance improvement, reaching a maximum capacity of 305 kN, an increase of approximately 7% over CB2, due to improved stress distribution and an increased moment arm.In general, it can be said that the presence of the openings causes a decrease in flexural strength due to the reduction in effective cross-sectional area, while the increased height partially mitigates this effect by increasing overall stiffness and improving internal force distribution. However, restoring full performance requires local structural solutions such as reinforcing the opening areas or increasing the density of shear connectors to achieve a more effective bond between the two materials.

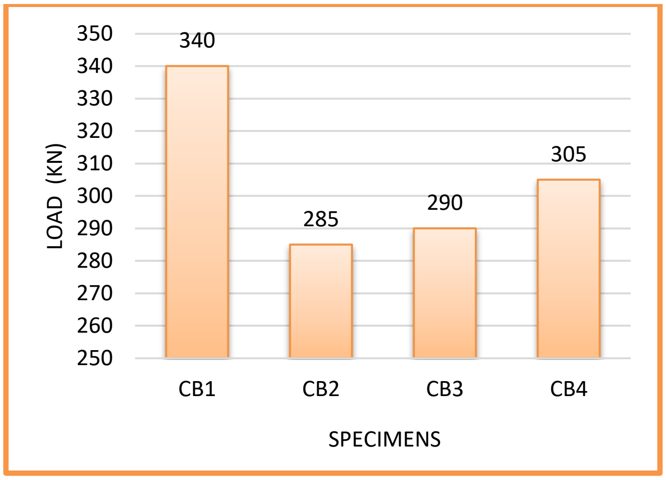


Figure 6. Ultimate Load Capacity of the Tested Composite beams.

3.2. Load-deflection curves

The load-deflection curves shown in figure 7 demonstrate the direct relationship between the flexural stiffness and the plastic behavior of the beams. All models followed elastic-plastic curves, but initial stiffness decreased significantly in the models with openings. In model CB1, the relationship was clearly linear up to approximately 80% of the maximum load, with a deflection of 4.64 mm at 340 kN, reflecting a robust composite interaction. CB2 exhibited a deflection of 7.26 mm at 285 kN, a 56% increase compared to the reference, due to the cross-sectional weakness in the opening area. In CB3, the deflection decreased to 6.89 mm at 290 kN, while CB4 recorded 6.39 mm at 305 kN, indicating a partial recovery of flexural stiffness with increasing height. These results highlight that the openings reduce stiffness and increase structural flexibility, while increasing the section height enhances flexural resistance and improves moment and stress distribution, while maintaining good ductility even after reaching the maximum load.

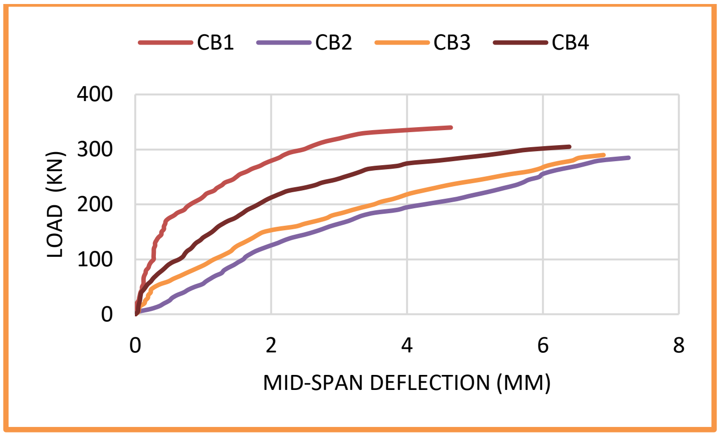


Figure 7. Load-deflection curves of the Tested Composite beams Specimens.

3.3. Load-Slip Curves

Interfacial slip between steel and concrete is an important indicator of shear bond efficiency. The curves in figure 8 showed that the presence of openings increased the amount of slip at all loading stages.Specimen CB1 recorded an ultimate slip of 0.628 mm, demonstrating excellent shear bond performance. CB2, on the other hand, recorded 1.428 mm, more than double the reference value, due to weak bonding in the opening area. CB3 also showed a slip close to 1.392 mm, while CB4 decreased to 0.946 mm, a clear improvement attributed to increased vertical stiffness and the ability to distribute forces within the section.Thus, it can be concluded that openings weaken the steel-concrete bond and increase relative deformations, while increasing the section height improves shear transfer behavior and reduces accumulated slip, enhancing the overall stability of the beam performance even in advanced plastic stages.

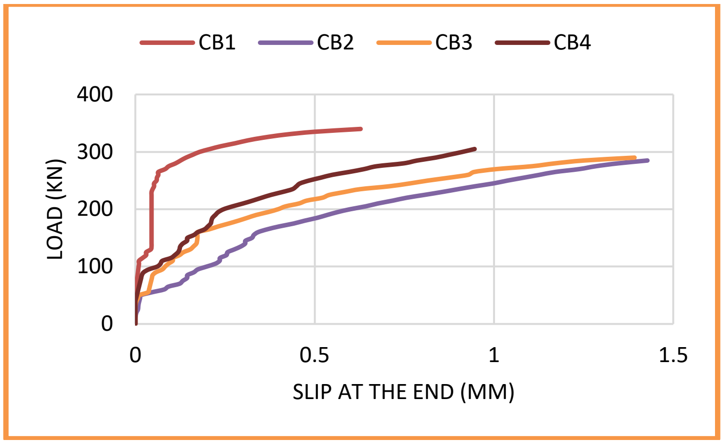


Figure 8. Load-Slip Curves of the Tested Composite beams Specimens.

3.4. Failure Modes

Direct observation and images analysis that show in figure 9 revealed that failure modes varied depending on the presence of openings and section height. Model CB1 exhibited a typical flexural failure with a mid-span plastic joint and limited diagonal cracks without separation between the steel and concrete. Model CB2 demonstrated a localized failure around the openings, with cracks concentrated in the area between the opening and the beam edge, with early onset of interfacial slip. Model CB3 exhibited less crack density, while Model CB4 exhibited a more uniform failure mode, with cracks concentrated in the region of maximum moment without significant separation between the two materials. It is concluded that the presence of openings shifts the failure mechanism from a uniform flexural mode to a localized failure centered around the perimeter of the openings, while increasing the height reverts the behavior to the more stable conventional flexural mode, increasing energy dissipation and maintaining the safety of the beam during the final stages of loading.

(a) Specimen CB1

(b) Specimen CB2

(c) Specimen CB3

(d) Specimen CB4

Figure 9. Composite beams after failure.

4. CONCLUSION

Effect of Openings: The presence of openings in a cold-formed steel section reduces flexural strength and initial stiffness by approximately 16%, resulting in a loss of effective cross-sectional area and the formation of local stress concentrations. Effect of Height: Increasing the section height from 300 to 400 mm improved structural performance and increased the maximum load to 305 kN, recovering a significant portion of the lost efficiency, achieving better stress distribution, and reducing slippage.Failure Mode: The failure mode changed from localized around the openings to stable flexural failure at higher heights, reflecting increased ductility and stability in the final stages of loading. Design Recommendation: It is recommended to strengthen the opening areas or increase the density of shear connectors to achieve an effective bond between the steel and concrete, ensuring safe and stable performance of composite beams in practical applications.

ACKNOWLEDGEMENTS

The author thanks the College of Engineering, University of Diyala, Department of Civil Engineering, for their academic support and provision of a suitable research environment for the completion of this work. He also thanks the Structural Testing Laboratory in the same department for its help with the study's practical part.

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