Experimental investigation of composite steel–concrete beams using symmetrical and asymmetrical castellated beams

Abstract: This study aims to investigate the behavior of concrete slabs acting compositely with symmetrical and asymmetrical castellated beams. Stud connectors are used to connect the concrete slab and steel section. The use of castellated steel beams to build up composite steel-concrete beams is now common practice in building construction. Five simply supported composite beams were examined under two-point loading. Two specimens built up from standard steel beams were used as control specimens and three specimens were built up from castellated steel beams. One of these specimens was built up using a castellated steel beam with an asymmetrical cross-section fabricated from two different standard sections (IPE120/HEA120). The concrete slab of all composite specimens had the same dimensions and properties. The experimental results showed that strength and rigidity were considerably greater for composite castellated steel beams compared to composite beams built up from the parent sections. The ultimate load capacity of a composite castellated beam fabricated from an IPE120 section was 46% greater than that of a composite beam built up using the parent beam, and the ultimate load capacity of a composite castellated beam fabricated from a wide-flanged HEA120 section resulted in an increase of 21% over the parent beam control specimen. The ultimate load capacity of the composite specimen built up using the asymmetrical castellated beam (IPE120/HEA120) achieved increases of 69% and 12%, respectively, compared to the control specimens built up from standard sections.

Keywords: Composite beam, castellated beam, vierendeel mechanism, web-post buckling

1 Introduction

In recent designs of long-span composite floors, castellated steel beams are designed to work compositely with the concrete floor slab, thus significantly increasing their ultimate load capacity. The composite castellated beam, consisting of a reinforced concrete slab connected to the castellated steel beams, is widely used in building construction around the world. The shear connections are used to ensure composite action between the slab and the beam, improving member stiffness and increasing ultimate load capacity. Some modern examples of projects using castellated beams for composite floor systems are shown in Figures 1 and 2 [1].
A castellated steel beam is formed by cutting the web of a standard beam and welding together the two halves generated by the cutting to create a structural member with greater depth than the parent beam. This manufacturing technique produces a system that combines an improvement in member strength with a decrease in member self-weight when compared to standard beams of similar strength. Another advantage of castellated beams is that they enable ducts, service pipes, and electrical cables to pass through the hexagonal web openings, thus eliminating the need to pass such services below the beams. The web openings also provide an aesthetic benefit when castellated beams are employed in buildings with exposed members [2].

The use of asymmetrical steel-concrete composite castellated beams has become extensive in construction practice due to improvements in strength-to-weight ratio. This study focuses on the effects of using an asymmetrical castellated beam to form the composite beam as seen in Figure 3 [3]. To improve the design performance, the bottom T-section of the castellated beam is cut from a heavier steel profile (e.g., HEB) than the beam the top T-section is cut from (e.g., IPE). The concrete reinforced slab takes the majority of the compressive stresses, whereas the steel beam carries most of the tension forces in a composite steel-concrete beam. The geometry of a composite section results in a stress distribution with the neutral axis located near the upper flange. Therefore, an increase in the thickness of the bottom flange will improve the ultimate load capacity of the composite beam. Extensive studies have been conducted on composite castellated beams [3].

Hosain and Speirs [4] tested twelve specimens of the castellated beam to study the effect of opening sizes on the failure mode. The results showed that the optimum size of the opening requires a minimum throat width to minimize the likelihood of failure due to Vierendeel bending. Nethercot and Kerdal [5] investigated the failure modes of castellated beams and concluded that the most likely modes of failure were a flexural mechanism, Vierendeel bending, web-post buckling, welded rupture in joints, and lateral-torsional buckling. Hartono and Chiew [6] carried out tests on composite half-castellated beams, which are fabricated using one half of a castellated beam with a horizontal flange plate welded to the top of the web-posts and shear studs welded to the plate. They observed web-post buckling failure in the steel section. Also, the performance of a half-castellated beam without a concrete slab was examined for comparison purposes. This specimen failed due to lateral-torsional buckling, demonstrating that adding a concrete slab to a beam considerably increases its ultimate load capacity. Lawson et al. [1] carried out experimental tests on four composite cellular beams with a symmetrical cross-section (fabricated from IPE400), in addition to the fifth specimen with asymmetrical cross-section fabricated from IPE400 and HEB340 to study the effect an asymmetrical cross-section has on failure modes. The results showed that asymmetry is a critical factor because it leads to increased bending moments in the web posts. Sheehan et al. [3] conducted testing on two groups of full-scale asymmetrical composite cellular beams with elongated openings at mid-span to investigate the modification to the composite action on the Vierendeel bending resistance at the web openings. The beams resisted a shear load that was 45% greater than the predicted shear resistance of the steel cross-section. Al-Thabhawee and Mohammed [7] studies the strengthening of the castellated beam with an octagonal opening by welding a circular ring inside of the web opening. This strengthening technique led to reinforcing the web portion and avoiding web-post buckling failure. The results have shown that the ultimate load at strengthening the web opening by circular ring increased up to 288% compared with the parent beam.

This research aims to give an overview of current developments in composite steel-concrete members and flooring systems as well as to illuminate trends for future research. The main objectives of research in this field are to study innovative construction methods and the best usage of construction materials, in addition to economic considerations towards sustainability and resilience.
Table 1: Details of steel beams used in the composite specimens

| Groups | Specimens | Type of steel beam | Castellated beam | Dimension (mm) |
|--------|-----------|--------------------|------------------|---------------|
|        |           | Top T-section | Bottom T-section | d | H |
| Series 1 | CNB-I | Standard section IPE120 | – | – | 120 | 190 |
|         | CNB-H | Standard section HEA120 | – | – | 120 | 190 |
| Series 2 | CCB-I | Symmetrical castellated beam | IPE120 | IPE120 | 170 | 240 |
|         | CCB-H | Symmetrical castellated beam | HEA120 | HEA120 | 170 | 240 |
| Series 3 | CCB-IH | Asymmetrical castellated beam | IPE120 | HEA120 | 170 | 240 |

Where d is depth of steel beam, and H is the overall composite specimen depth.

Figure 4: Dimensions of typical concrete flange of composite specimens

2 Experimental program

2.1 Testing program

Three series of tests were carried out on simply supported composite concrete-steel beams at Kufa University laboratories. The dimensions of each of the specimens are shown in Table 1. Each specimen had a clear span of 1800 mm, and the concrete slab was 70 mm thick and 350 mm wide. Minimum steel (to ACI code requirements) was placed in each direction to reinforce the concrete slab. The dimensions and reinforcement details of the typical concrete slab used for each composite specimen are shown in Figure 4.

In Series 1, two control specimens were built up using standard hot-rolled sections. The first specimen, CNB-I, used a standard IPE120 I-section (total depth 120 mm, flange width 64 mm, web thickness 4.4 mm, and flange thickness 6.3 mm), while the second specimen, CNB-H, was built up using a HEA120 wide flange section (total depth 120 mm, flange width 120 mm, web thickness 5 mm, and flange thickness 8 mm). Figure 5a shows the dimensions and details of CNB-I and CNB-H.

Series 2 consisted of two specimens, CCB-I and CCB-H, built up using symmetrical castellated beams. The first specimen, CCB-I, used a castellated beam fabricated from an IPE120 section, resulting in a beam depth of 170 mm without adding any weight. The increase in depth of the castellated beam with respect to the parent section, referred to as the expansion ratio, was 42%. The second specimen, CCB-H, used a castellated beam fabricated from a HEA120 wide flange section, also resulting in a beam depth of 170 mm. The castellated beams of both Series 2 specimens have identical expansion ratios and dimensions of hexagonal openings, as shown in Figure 5b.

Series 3 consisted of one specimen, CCB-IH, built up using an asymmetrical castellated steel beam. This specimen used a castellated beam fabricated from two different steel sections. The top T-section was cut from an IPE120, while the bottom T-section was cut from a HEA120 wide flange section, providing a beam depth of 170 mm. To facilitate comparison, all symmetrical and asymmetrical castellated beams used in the study had identical expansion ratios of 0.42. Figure 5c shows the dimensions and details of Specimen CCB-IH. The details of each tested composite specimen are listed in Table 1.
Figure 5: Dimensions and details of composite steel-concrete specimens
2.2 Material properties

All composite specimens were constructed from the same bare steel to ensure the use of beams with identical material properties in each of the series of tests. The concrete flange of all cases was made using the same concrete mixture. Crushed coarse and natural fine aggregate was used with ordinary Portland cement to produce this mix. A set of three concrete cubes (150 × 150 × 150 mm) were tested to obtain the compressive strength. The average of concrete compressive strength of these cubes was 30.4 MPa. The reinforcement of the slab consisted of 4 mm wire mesh reinforcement with a yield strength of 410 MPa. Three tensile specimens cutting from the flange and web of IPE120 as well as web of HEA120 sections were tested. The standard dimensions of the steel specimen were specified by ASTM E-8M. In accordance with ASTM A 370-17, steel specimens were tested by universal testing machine which has a load capacity of 590 kN as shown in Figure 6. The ultimate stress, yield stress and elasticity modulus that recorded from the universal testing machine were listed in Table 2.

![Steel specimens](image1)

![Universal Testing Machine](image2)

Figure 6: Tensile test of steel

The connection between the concrete slab and steel beam was achieved in all composite specimens by shear connectors of 14 mm diameter and height 50 mm welded to the top flange of the steel beam, as shown in Figure 7. The shear studs were distributed in a single row along the length of the steel beam at a spacing of 200 mm.

2.3 Instrumentation and loading

All the composite specimens were put on simple supports located 50 mm from both ends and were tested under two-point loads as shown in Figure 8. A hydraulic jack with 1000 kN capacity was used to apply a monotonic load to the concrete slab of the composite beams. Vertical displacement at the mid-span of the specimens was measured using an LVDT gauge and an electronic dial. Two-point loading was adopted in this test to ensure constant pure bending in the middle 600 mm portion of each specimen.

![Welding of the studs](image3)

Figure 7: Welding of the studs on flange of steel beams

![Test setup](image4)

Figure 8: Test setup of Specimen CCB-H

| Specimens | $f_y$ (MPa) | $f_u$ (MPa) | $E$ (MPa) |
|-----------|-------------|-------------|-----------|
| SP-1      | 305.7       | 556.1       | 2.01×10^5 |
| Sp-2      | 305.1       | 551.7       | 2.03×10^5 |
| SP-3      | 304.4       | 543.2       | 2.07×10^5 |
| Average   | 305.1       | 550.4       | 2.0367×10^5 |
Table 3: Experimental results of composite specimens

| Groups   | Specimens | Type of Steel Beam | First crack load (kN) | Ultimate load at failure (kN) | Maximum slip (mm) | Failure mode                       |
|----------|-----------|--------------------|-----------------------|-----------------------------|-------------------|-----------------------------------|
| Series 1 | CNB-I     | Standard section   | 25                    | 110                         | 10.3              | Compression failure in concrete slab |
|          | CNB-H     | Standard section   | 35                    | 165                         | 9.3               | Compression failure in concrete slab |
| Series 2 | CCB-I     | Symmetrical Cast.  | 30                    | 160                         | 14.2              | Vierendeel bending in steel beam    |
|          | CCB-H     | Symmetrical Cast.  | 45                    | 200                         | 10.2              | Web-post buckling in steel beam     |
| Series 3 | CCB-IH    | Asymmetrical Cast. | 40                    | 186                         | 13.10             | Vierendeel bending at top T-section of steel beam |

3 Results

In this research, the tests were designed to study the influence of castellated steel beams used in composite steel-concrete beams as well as to investigate the influence of castellated beams on the asymmetrical cross-section. The experimental results, such as mid-span deflection, ultimate load capacity, failure modes, and maximum slip are discussed in the following paragraphs. The results are listed in Table 3.

3.1 Composite beams with IPE120 sections

Specimens CNB-I and CCB-I were examined to study the effect of using castellated steel beams on the behavior of composite beams. An IPE120 section was used to build up Specimen CNB-I, and an IPE120 section was used to fabricate the castellated beam (expansion ratio 0.42) used to build up Specimen CCB-I. Figure 9 shows that Specimen CNB-I failed in the flexural failure mode. The first crack occurred in the concrete slab at 25 kN, and flexural cracking increased as the test load increased, up to failure at ultimate load capacity 110 kN due to crushing of the concrete slab.

The load applied to Specimen CCB-I exceeded the failure load of CNB-I (110 kN) and continued until failure occurred at an ultimate load of 160 kN due to Vierendeel bending failure of the castellated steel beam, as shown in Figure 10. In general, Figure 11 illustrates the sequence of yield points in the failure region. Based on the test observations, the first sign of yielding was identified at Point 1, at an applied load of 153 kN. As the applied load approached 157 kN, yielding was observed at the corner of the hexagonal opening at Point 2, then at the opposite corner at Point 3. The yielding continued until failure occurred due to Vierendeel bending at an ultimate load of 160 kN.

The composite beam built up from a castellated beam (CCB-I) had an ultimate load capacity 46% greater than that of the composite beam built up from the parent beam (CNB-I). This increase in ultimate load capacity was due to the neutral axis of the composite cross-section of CNB-I occurring closer to the concrete slab than for CCB-I. The
load-deflection curves of CNB-I and CCB-I specimens are shown in Figure 12. In the case of Specimen CCB-I, flexural stiffness has improved significantly because the castellated beam is deeper than the parent section.

3.2 Composite beams with HEA120 sections

Specimens CNB-H and CCB-H were tested to study the effect of using wide-flange castellated beams on the behavior of composite steel-concrete beams. A HEA120 section was used to build Specimen CNB-H, and an HEA120 section was used to fabricate the castellated beam (expansion ratio 0.42) used to build Specimen CCB-H. In specimen CNB-H, the first crack happened at 35 kN, and flexural failure
Figure 15: Web-post buckling due to shear force

Figure 16: Load-deflection curve of Specimens CNB-H & CCB-H

Figure 17: Failure mode of Specimen CCB-IH

(by crushing of the concrete slab) occurred at an applied load of 165 kN, as shown in Figure 13.

The CCB-H specimen failed due to web-post buckling of the castellated beam at an ultimate load of 200 kN, as shown in Figure 14. This failure mechanism occurred due to high shear forces twisting the web posts. As illustrated in Figure 15, the horizontal shear forces at mid-depth of the web post \( V_{h} \) cause compressive and tensile stresses due to bending near the top and bottom of the web post. These stresses vary depending on the hexagonal opening and the angle of maximum stress varies depending on the width of the web post. The load-deflection curves of Specimens CNB-H and CCB-H, shown in Figure 16, demonstrate the improved performance of the composite specimen built up from a castellated beam. The ultimate load capacity of CCB-H is 21% greater than that of CNB-H.

3.3 Composite beam with an asymmetrical castellated beam

Specimen CCB-IH was built up using an asymmetrical castellated beam fabricated from IPE120 and HEA120 sections. Testing of this specimen was conducted to investigate the effect of using asymmetrical castellated steel beams on the behavior of composite beams. The first sign of yielding was observed in the corners of the hexagonal web opening at an applied load of 180 kN and yielding continued until failure occurred at ultimate load 186 kN due to Vierendeel shear in the top T-section (IPE120) together with web post-buckling (see Figure 17). The shear force in the top T-section was resisted by Vierendeel bending, and the remaining shear force was resisted by the heavier bottom T-section. The load-deflection response of specimen CCB-IH combined with those of the other specimens is shown in Figure 18. The ultimate load capacity of Specimen CCB-IH...
is greater than that of CNB-I and CNB-H by 69% and 12%, respectively.

![Load-deflection curves of all specimens](image)

**Figure 18:** Load-deflection curves of all specimens

### 4 Conclusions

In general, the strength (and, therefore, the rigidity) of composite steel-concrete beams increased considerably when using castellated beams compared to when using the standard parent section, because the overall depth of the steel beam was increased without adding any material. When composite steel-concrete beam was produced using a castellated beam fabricated from an IPE120 I-section, the ultimate load capacity increased by 46% over a composite beam built using the standard IPE120 beam. The corresponding increase in ultimate load capacity when using a HEA-120 H-section as parent beam was 21%. From the results of the experimental study, it can be noted that an asymmetrical castellated beam fabricated from IPE120 and HEA120 to build up a composite steel-concrete led to increases in the ultimate load capacity of 69% and 12%, respectively, over that of composite beams built up using standard IPE120 and HEA120 sections.

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