Ultimate strength capacity of composite self-compacting castellated steel beams

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Abstract. Castellated steel profile sections can be used in order to increase the flexure strength of composite concrete-steel beams for building large spans. Castellated beams are fabricated by cutting I-section steel girders in a special manner before welding to produce an opening throughout the web. The depth of the new section is enhanced by a specific percentage, which increases the performance of the beam against bending. Castellated beams can be used compositely in long span floors where floor beam heights are kept to a minimum by passing services through the web-openings. This paper will focus on the composite behaviour of specimens in two types of concrete with different strengths. The ultimate strength for these types of structures with different degrees of castellation will be considered. The study consisted of two parts: the first part tested six specimens using push out test specimens to understand the real behaviour of their shear connectors. The second part tested eight specimens under a third point static load. Three of the push out test specimens were of normal concrete, and the others were self-compacting concrete.

Four of the composite beam specimens were normal concrete slabs, while the other four specimens were made from self-compacting concrete. The experimental programme also included fabrication of I-section steel beams with different castellation degrees of 0%, 25%, 33.8%, and 50%. The effects of concrete type and degree of were thus studied. It was found that the maximum load capacity was significantly affected by these parameters such that it was increased with both the increase of compressive strength of the concrete and the degree of castellation. The push out test showed that the slip behaviour was linear below 70 to 80% of the ultimate load capacity. At this linear stage, the amount of slip is very low and rarely exceeds 0.5 mm.

Keywords: Castellated steel beams, self-compacting concrete, experimental investigation, push out test, bond slippage.

1. Introduction

In recent years composite constructions have become more important due to their known properties of withstanding loads, reducing the depth of structural members compared to non-composite alternatives, and reducing weight of the overall structure as a result optimum usage of materials. Castellated beams can also be used compositely in long span floors, allowing floor heights to be kept to a minimum by passing the services through the web-openings. The use of composite beams in multi-storey buildings enables structural engineers to offer larger uninterrupted floor spans. Many other features may be obtained when using composite castellated beams and increasing the height of the section such as enhancements of the section modulus, the moment of inertia, stiffness, and flexure resistance, as well as reducing the weight of profile and cutting down the cost of the whole structure by removing need for
plate girders and using the openings to pass services, ultimately reducing the overall thickness of the floor [1]. The first research into castellated beams was in 1959 by [2]. They noted that castellated beams under pure bending yielded primarily in the upper and the lower tee sections of the web openings. The first known researchers to test composite castellated beams were in 1964 [3], who tested six castellated beams using spiral shear connectors. The tested specimens were loaded with a distributed load until failure of the web with post-buckling and the appearance of transverse cracks in the concrete. They thus concluded that the neutral axis in the web post was lower than that associated with the web openings. In 1997, [4] numerically and experimentally tested five composite castellated beams of different lengths and varying shear to moment ratios in order to discuss flexural and shear behaviour. It was observed that the longer castellated beams displayed lateral torsional buckling in the compression flange, whereas the other beams failed when lateral torsional buckling was seen in the web post. In 2007, [5], submitted a static analysis with partial interaction for composite girders. This analysis considered the interlayer slip due to including accurate boundary conditions. Although this produced an exact solution, the work was extremely long and intensive, and the results required simplification. In 2014, [6] developed an efficient nonlinear model using Abaqus software to analyse continuous composite castellated beams with partial interaction. Good agreement was noticed between previous experimental data and the numerical results obtained. They used stiffeners at different locations, and concluded that the ultimate load capacity of the beams increased by 12%, 25%, and 17% after applying vertical stiffeners, starting the openings after the region of the negative moment, and applying stiffeners around the web openings, respectively.

2. Testing Program
The experimental tests in this research included push out specimens and composite beam specimens. The processes utilised to fabricate the castellated beams are illustrated, and the properties of the steel components and concrete used listed below. The load test properties and instruments are also shown.

2.1 Push Out Test
This test was executed to estimate the shear strength and overall behaviour of the shear connectors (headed studs) used in the experimental work. The required dimensions were prepared as recommended by British code 5400-1979[7]. The width of slab used was 70 mm, as it was found that a narrow width of concrete slab may be used in push-out tests with high strength shear connectors[2]. Six specimens for the push out test were thus prepared, cast, and tested. Three were cast with normal concrete and the other three specimens were cast with self-compacting concrete. The material properties and mix proportions of the concrete were the same for the composite beams. The push-out specimen was composed of a 560 mm height steel beam linked on both sides to a concrete slab (460 mm × 300 mm) by two pairs of shear connectors. A steel plate of thickness 8 mm was attached at the upper end of the specimen to distribute the load. All details are shown in Figure 1. A Hydraulic Testing Machine with a loading capacity of 400 kN was used to test these specimens. The loads were subjected incrementally up to failure. Mechanical dial gages with a sensitivity of 0.01 mm were put on the steel section to measure the slip of the concrete slab from steel at each load increment. The recorded load verses slip was plotted for every specimen.
2.2 Beams Test

The total number of the composite beams tested experimentally was eight. Half of the beams were cast with normal concrete and the other half were cast with self-compacting concrete. The steel for two specimens was solid, whereas the others six specimens were castellated with different degrees of castellation (25%, 33.8%, and 50%). Two pairs of stiffeners were welded at the support region and another two pairs were welded at the two-thirds location of the I-steel beam. The composite beams were subjected to a static load at the two-thirds points of the span and tested experimentally. The dimensions of the I-steel sections used were \( d = 137.5 \) mm, \( b_f = 71 \) mm, \( t_f = 4.1 \) mm, and \( t_w = 5.1 \) mm for all solid specimens and for fabrication of the castellated specimens.

Table 1 shows the identifications and dimensions of the specimens. The clear span of each beam was 1428 mm. The width of the concrete used to prepare the composite beams was 350 mm and the thickness was 70 mm. Steel reinforcement of the concrete slab was designed according to the ACI-code[8], which demanded one layer of 6 mm deformed bars at 155 mm in the longitudinal direction, and at 158 mm in the transverse direction. Partial connection was achieved by using stud shear connectors with shank diameter 10 mm and length 55 mm welded to the middle of the top flange at 79.3 mm in one row.

Table 1. The Identification and Dimensions of the Specimens.

| Identification | Description          | \( d \) (mm) | \( a \) (mm) | \( h_o \) (mm) | \( h_p \) (mm) | \( S \) (mm) | \( \lambda \) (%) | \( D \) (mm) |
|----------------|----------------------|--------------|--------------|--------------|--------------|-------------|-----------------|-------------|
| SS1            | Solid beam - NC      | 137.5        | ---          | ---          | ---          | ---         | 0               | ---         |
| SS2            | Solid beam - SCC     | 137.5        | ---          | ---          | ---          | ---         | 0               | ---         |
| C1S1           | Castellated 25% - NC | 137.5        | 39.67        | 68.7         | 51.52        | 119         | 25              | 171.75      |
| C1S2           | Castellated 25% - SCC| 137.5        | 39.67        | 68.7         | 51.52        | 119         | 25              | 171.75      |
| C2S1           | Castellated 33.8% - NC| 137.5       | 52.89        | 91.61        | 45.59        | 158.67      | 33.8            | 183.83      |
| C2S2           | Castellated 33.8% - SCC| 137.5      | 52.89        | 91.61        | 45.59        | 158.67      | 33.8            | 183.83      |
| C3S1           | Castellated 50% - NC | 137.5        | 79.33        | 137.41       | 34.33        | 238         | 50              | 206.1       |
| C3S2           | Castellated 50% - SCC| 137.5        | 79.33        | 137.41       | 34.33        | 238         | 50              | 206.1       |

\( \lambda \): Degree of castellation
2.3 Fabrication Procedures

The fabrication procedure used to manufacture the castellated beams required the use of a special cutting machine (CNC). After that, the two parts of the steel sections were connected and welded in a manner that created hexagonal cells inside the web. The dimensions were decided according to the following equations:

\[ D = d \times (\lambda + 1) \times 100 \]  
(1)

\[ a = \frac{(D - d)}{\sin 60} \]  
(2)

\[ h_p = \frac{d - a \times \sin 60}{2} \]  
(3)

where

- \( a \) = Throat width (the length of one side of hexagonal cells)
- \( h_p \) = Throat depth (the height of the point where cutting through the web starts)

Figures 3 to 6 show the details and dimensions of the composite beams fabricated in the present work as subjected to static load.

Figure 3. Details of Composite Beam-Solid I-Section.
2.4 Properties of Steel Components
Several different types of steel objects were used, including I-steel beam, stiffeners, stud connectors, and reinforcements. Their properties are summarised in Table 2.
Table 2. Properties of steel components used.

| Material            | Description          | Unit   | Value   |
|---------------------|----------------------|--------|---------|
| I-beam section      | Yield strength       | MPa    | 322.33  |
|                     | Ultimate tensile     | MPa    | 466.67  |
|                     | strength             |        |         |
|                     | Modulus of elasticity| MPa    | 201003  |
|                     | Elongation           | %      | 9.42    |
|                     | Head diameter        | mm     | 17      |
|                     | Shank diameter       | mm     | 10      |
|                     | Length               | mm     | 55      |
| Studs connectors    | Yield strength       | MPa    | 447.67  |
|                     | Ultimate tensile     | MPa    | 696.67  |
|                     | strength             |        |         |
| Reinforcement bar   | Yield strength       | MPa    | 670     |
|                     | Ultimate tensile     | MPa    | 738     |
|                     | strength             |        |         |
|                     | Equivalent steel bar | mm     | 5.96    |

2.5 Preparation of Normal Concrete and Self-Compact Concrete

Normal type concrete materials include cement, fine aggregate, coarse aggregate, and water which all conformed to Iraqi specifications for 1985[9]. For the self-compacting concrete, the concrete materials included cement, fine aggregate, coarse aggregate, limestone powder, a High Range Water Reducing Agent (HRWRA) super plasticizer called Sika ViscoCrete hi-tech 1316, and water, which also conformed to the Iraqi 1985 specifications and ASTM specifications[10].

The normal concrete mixture was designed according to BS to achieve a compressive strength of concrete of $f'_{c}=35$MPa. A self-compacting concrete mixture was designed according to the European Guidelines for Self-Compacting Concrete (EFNARC)[11], to achieve a compressive strength of concrete of $f'_{c}=50$MPa. To verify adherence to the production mix of fresh concrete, every trial mix was subjected to many tests, including Slump-flow, V-funnel, and L-box tests for self-compacting concrete, and slump for normal concrete.

Greasing of moulds was performed before casting the concrete mixture. The normal concrete was compacted, while there was no need for compaction of the self-compacting concrete. All specimens were immersed in water for 28 days, while the cubes, cylinders, and prisms were used in hardened concrete tests. Figure 7 shows the preparation of specimens for concrete casting, while Figure 8 represents the concrete samples prepared for the hardened concrete test.
Table 3. Mechanical properties of hardened concrete.

|                        | Self-compact concrete | Normal concrete |
|------------------------|-----------------------|-----------------|
| $f_{cu}$               | 61.1                  | $f_{cu}$ 46     |
| $f'_c$                 | 51.8                  | $f'_c$ 35.4     |
| $f_r$                  | 8.04                  | $f_r$ 4.97      |
| $f_{sp}$               | 3.79                  | $f_{sp}$ 3.03   |
| $E$                    | 34000                 | $E$ 30000       |

2.6 Static Load Test Properties and Instruments
A load was applied in increments of 5 kN on the beams up to failure using a hydraulic testing machine with a load capacity of 400 kN; the deflection was recorded using dial gages at the mid span and third points of the simply supported beams.

Figure 7. The preparation of specimens for concrete casting.
Figure 8. The concrete samples prepared for a hardened concrete test.
3. Results and Discussion

3.1 Push-Out Test Results

Figures 10 and 11 show the results for the self-compacting specimens and normal concrete specimens, respectively. The force is given for one stud connector, as the recorded force was divided by the number of studs in each specimen, which was four. According to Eurocode[12] the shear resistance of a stud shear connector with (h/d ≥ 4) used in a solid slab is specified as the smaller of Equation 4 or 5:

\[ P_{rd1} = \frac{0.8 F_u \left( \frac{\pi d^2}{4} \right)}{Y_v} \]  
\[ P_{rd2} = \frac{0.29 d^2 \sqrt{f_{ck} E_{cm}}}{Y_v} \]  

where

- \( P_{rd1}, P_{rd2} \) are the permissible shear capacities of studs (N);
- \( F_u \) is the ultimate tensile strength of the stud \( \left( \frac{N}{mm^2} \right) \);
- \( Y_v \) is a factor (here, 1.25);
- \( d \) is the shank diameter of a stud (mm);
- \( f_{ck} \) is the cube compressive strength of concrete \( \left( \frac{N}{mm^2} \right) \); and
- \( E_{cm} \) is the modulus of elasticity of concrete \( \left( \frac{N}{mm^2} \right) \).

Equation 4 is related to the characteristics of the stud used, and in this case gives 37.1 kN, while equation 5 is related to the characteristics of the concrete used; for normal concrete, this gives 27.25 kN, while for self-compacting concrete it is 33.44 kN. For specimens cast with normal concrete, the average experimental shear capacity is 32.8 kN, and for specimens cast with self-compacting concrete, the average value of the three specimens is 39.73 kN. These equations may thus be considered conservative. It is clear that the maximum load capacity of the self-compacting specimens is 40.5 kN, with maximum slip before the fracture being 3.83 mm; the maximum load capacity for normal concrete specimens is 33.5 kN with maximum slip just before the fracture of 3.4 mm. The push out test showed that the slip...
behaviour was linear below 70 to 80% of the ultimate load capacity. At this linear stage, the amount of slip is very low and rarely exceeds 0.5 mm. This suggests that there is a large bond between the self-compacting concrete and the shear connectors, and that this bond is decreased in specimens cast in normal concrete with the same dimensions.

3.2 Composite Girders Results
3.2.1 Force-deflection relationships
As mentioned, the displacements were recorded in the mid-span and third-span.
I. Mid-span force-deflections
The load versus deflections at the mid-span of all eight specimens were recorded and are given in Figures 12 to 15; each figure introduces the results of two specimens, one of self-compacting concrete and the other of normal concrete. The straight line represents the service deflection dependent on the beam length ($L/360$).

![Figure 10. The Load-Slip Relationship of SCC Push-Out Specimens.](image)

![Figure 11. The Load-Slip Relationship of NC Specimens.](image)

![Figure 12. Load-Deflection Diagram of Solid Composite Beam Specimens.](image)

![Figure 13. Load-Deflection Diagram of Composite Castellated Beam Specimens (25%).](image)
3.2.2 The effects of castellation

The composite solid beam introduces a relatively continuous force versus deflection relationship for specimens cast both with normal concrete and self-compact concrete. However, for the composite castellated beams, the test was stopped early and there is less continuity in the force versus deflection curves, especially for specimens cast with normal concrete. It is worth mentioning that, during the test of castellated beams, the concrete slabs suffered from large cracks and crushing, and thus were considered failed, despite the fact that the castellated steel I-beam appears to still be able to resist greater loads.

This can be attributed to the calculation of the width of the concrete slab, which was calculated based on the composite solid beam specifications. It can be concluded that specifications for designing a castellated beam must be different. A preliminary suggestion may be increasing the width or height of the concrete slab, or the strength of the concrete to make it compatible with the castellated steel beam. This situation is less pronounced with specimens cast with self-compact concrete, and thus using self-compact concrete is one of the solutions which may be considered suitable for this type of steel girders.

All the previous analysis is reflected in Figures 16 and 17. Performing deep analysis and taking 60% of the ultimate capacity of the solid composite girders as a horizontal reference line (60% of the ultimate load can be considered a standard working load), this is 117 kN for specimens cast with self-compact concrete and 100.8 kN for specimens cast with normal concrete; several status changes can then be noted. The vertical reference line is the service deflection (L/360), and the behaviour of solid girders for both specimens (cast with normal or self-compact concrete) shows more ductility than the other specimens, reflected in longer force versus deflection curves; however, they reach the working load at impermissible deflections. The percentages of decrease of deflection at permissible loads and service deflections for composite castellated girders cast with normal concrete are 9.32%, 24.43%, and 39.55% for the various degrees of castellation 25%, 33.8%, and 50% respectively. For composite castellated girders cast with self-compact concrete, the percentages of decrease of deflection at the same levels are 4%, 20.65%, and 35.77%, respectively, for the various degrees of castellation 25%, 33.8%, and 50%.

Although the composite castellated specimens did not provide more ultimate load due to the reasons presented, all the specimens had acceptable or lower deflection at the specified working load.

![Figure 14](image1.png) ![Figure 15](image2.png)

**Figure 14.** Load-Deflection Diagram of Composite Castellated Beam Specimens (33.8%).

**Figure 15.** Load-Deflection Diagram of Composite Castellated Beam Specimens (50%).
3.2.3 Bond slippage

The difference between the longitudinal deformation of the concrete slab and steel beam in a composite girder is known as the slip. The slip behaviour of all beams is shown in Figures 18 to 21; each figure introduces the force versus slip of two specimens, one cast with self-compacting concrete and the other cast with normal concrete.

Figure 16. Load-deflection diagram of composite beam specimens with SCC.

Figure 17. Load-deflection diagram of composite beam specimens with NC.

Figure 18. Load-Slip Diagram of Solid Composite Beam Specimens.

Figure 19. Load-Slip Diagram of Composite Castellated Beam Specimens (25%).

Figure 20. Load-Slip Diagram of Composite Castellated Beam Specimens (33.8%).

Figure 21. Load-Slip Diagram of Composite Castellated Beam Specimens (50%).
3.2.4 The effect of degree of castellation

The degree of castellation has a distinct influence on the behaviour of composite beam specimens, as mentioned previously. The effect of this parameter on slip behaviour was thus studied separately. This investigation was done at the ultimate state and also at 60% of the ultimate load of the solid beam. The slip behaviour of composite girder specimens cast with self-compacting concrete and normal concrete are shown in Figures 22 and 23, respectively. Generally, at the ultimate stage, the slip magnitude decreases as the degree of castellation increases.

At 60% of the ultimate load of the solid composite beam, the slip behaviour was analysed, and the percentages of slip decreases were 14.71%, 26.47%, and 35.29%, respectively, for each of the degrees of castellation 25%, 33.8%, and 50% for specimens cast with self-compacting concrete. For specimens cast with normal concrete, the percentages of slip decrease were 13.97%, 28.57%, and 36.51% respectively, for the same degrees of castellation.

![Figure 22. Load-Slip Diagram of Composite Beams Specimens with SCC.](image1)

![Figure 23. Load-Slip Diagram of Composite Beams Specimens with NC.](image2)

3.2.5 The effect of concrete type

In most instances, variation of concrete strength or type produces a difference in behaviour. The magnitude of slip is different among composite specimens cast with self-compacting concrete and specimens cast with normal concrete. At the ultimate stage, the comparison may be considered illogical, however, because of the difference in ultimate load. Thus, such comparisons may be done at 60% of the ultimate capacity of solid composite girders cast with normal concrete, which is 100.8 kN, and the comparison therefore can be done between a specimen cast with normal concrete and another cast with self-compacting concrete but otherwise identical specifications. The percentage decrease of slip for a solid composite girder is 21.15% when using self-compacting concrete, while the decreases in percentage of slip for castellated composite girders when using self-compacting concrete are 29.05%, 26.62%, and 25%, respectively for the various degrees, slightly larger than the percentage of slip decrease for the solid composite beam.
4. Conclusions
According to the experimental work in the present study, several conclusions can be drawn:

- The percentages of decrease of deflection at permissible load and service deflection for composite castellated girders cast with normal concrete are 9.32%, 24.43%, and 39.55% for the degrees of castellation 25%, 33.8%, and 50% respectively. For composite castellated girders cast with self-compacting concrete, the percentages of decrease of deflection at the same levels are 4%, 20.65%, and 35.77%, respectively.

- The percentages of slip decreases were 14.71%, 26.47%, and 35.29% for degrees of castellation 25%, 33.8%, and 50%, respectively, for specimens cast with self-compacting concrete. For specimens cast with normal concrete, the percentages of slip decrease were 13.97%, 28.57%, and 36.51%, respectively, for the same degrees of castellation.

- The percentage of decrease of slip for solid composite girders is 21.15% when self-compacting concrete is used, while the decrease in percentage of slip for castellated composite girders at 25%, 33.8%, and 50% degrees of castellation using self-compacting concrete are 29.05%, 26.62%, and 25%, respectively, slightly larger than the percentage of slip decrease for a solid composite beam.

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