Experimental study of composite concrete cellular steel beams

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ABSTRACT:
The main objective of this study is to compare the structural behavior of composite steel–concrete beams using cellular beams with and without steel ring stiffeners placed around the web openings. An IPE140 hot rolled 1-section steel beam was used to create four specimens: one without openings (control beam); one without shear connectors (non-composite); a composite steel–concrete beam using a cellular beam without strengthening (CLB1); and a composite steel–concrete beam using a cellular beam (CLB4-R) with its openings strengthened by steel ring stiffeners with geometrical properties Br = 37mm and Tr = 5mm. CLB1 was fabricated with openings of 100mm diameter and a 1.23 expansion depth ratio, while CLB4-R was fabricated with openings of 130mm diameter, a 1.42 expansion depth ratio. Both beams were 1700mm in length with ten openings. The results of this experiment revealed that the loads applied to CLB1 and CLB4-R at deflection L/360 exceeded the load applied to the control specimen at the same deflection by 149.3% and 177.3%, respectively. The results revealed that the non-composite beam had an ultimate load 29% lower than that of the control beam. The ultimate load on CLB1 was 5.3% greater than that of the control beam, and failure occurred due to web-post buckling. While the ultimate load of the CLB4-R beam was 18.43% greater than that of the control beam, the Vierendeel mechanism was indicated as the failure mode.

1- INTRODUCTION

The use of cellular beams is popular in tall buildings to provide optimization of storey height by allowing passage through the webs for ducts, cables, and other utilities, thus reducing the height of the floor assembly. Cellular beams consist of steel sections with distributed circular web openings. They are produced by a specified fabrication process starting with a double cutting line with a semicircular path along the web panel of the parent section, then the parts are rejoined to produce a beam with circular opening shapes in the web. This process can be used to increase the section depth by up to 50% compared with the parent section [1], which leads to an increase in elastic stiffness and flexural strength’ as shown in Figure 1. The existence of web openings may cause different failure types [2], for example, the Vierendeel mechanism, welded joint rupture, and web-post buckling, that occur as the result of shear forces additional to failure modes which occur in solid web steel beams, such as the flexural mechanism and lateral–torsional buckling. These types of failure happen because of instability in the web area. The current study intends to investigate the improvement in structural behavior of cellular steel beams by adding a ring stiffener around the circular web opening, as shown in Figure 2, to avoid web-post buckling failure and increase the resistance of composite steel–
concrete beams. Four experimental specimens were tested in the Engineering College Labs of Kufa University.

![Fabrication procedure for cellular beams](image1)

**Figure 1:** Fabrication procedure for cellular beams

![Steel ring stiffeners around web openings](image2)

**Figure 2:** Steel ring stiffeners around web openings

Erdal and Saka [3] tested twelve cellular beams that were simply supported. The failure mode for the two unconstrained NPI 240 beams was lateral–torsional buckling, while the failure mode for the other two beams was web buckling. The failure mode for the NPI 260 and NPI 280 beams was the Vierendeel mechanism and web-post buckling, respectively. Oukaili and Abdullah [4] tested to failure nine composite steel–concrete beams utilising two distinct strengthening techniques: intermediate stiffeners only, and exterior prestressing plus intermediate stiffeners. Adding intermediate stiffeners boosted load-carrying capacity by 21.8% for specimens subjected to pure bending, 33.3% for specimens subjected to combined flexure and torsion, and 4.44% for specimens subjected to pure torsion. The load-carrying capacity was increased by 134.3%, 116.6%, and 4.88%, respectively, using the second strengthening technique. For specimens under pure bending and combined flexure and torsion, the first technique reduced midspan deflections under service loads by 22% and 13%,
respectively, compared to specimens under pure bending and mixed flexure and torsion. Al-Thabawee and Al-Hassan [5] focuses on putting a steel ring inside octagonal openings to strengthen the web, which is the weakest part of the structure, in order to attain high strength at a reasonable cost. A hot-rolled standard section IPE140 parent section was used to fabricate nine castellated steel beam specimens and one control beam. The results show that the steel ring effectively reinforces the web posts.

2- EXPERIMENTAL WORK

2-1 Description of specimens

Four specimens of steel–concrete composite beams were studied. The concrete used in all the specimens had normal compressive strength. The details of the tested beam specimens are shown in Table 1.

All beams had a topping slab with the same cross-sectional dimensions of 400mm x 80mm. A hot-rolled I-section steel beam (IPE140) was used as the parent section for the four specimens: the control beam (composite); and the second beam (non-composite); CLB1, a cellular steel beam with openings of diameter Do = 100mm, expansion depth ratio D/d = 1.23, and spacing ratio S/Do=1.7; and CLB4-R, a cellular steel beam with openings of diameter Do = 130mm, expansion depth ratio D/d = 1.43, and spacing ratio S/Do = 1.3. All specimens had the same flange thickness (tf = 7mm), web thickness (tw = 5mm), ’flange width (bf = 74mm), and span length (L = 1700mm). Specimen CLB1 had no strengthening. CLB4-R was strengthened with steel ring stiffeners with Br =37mm and thickness Tr = 5mm. Tension testing on coupon specimens in accordance with ASTM A370 [6] was used to determine the material properties. A plasma CNC cutting machine was used to make the semicircular cutting lines along the web of the parent section to produce two parts with T-sections. The two parts were rejoined using electrode welding to form a cellular beam with circular web openings, as shown in Figure 3.

![Figure 3: Cutting by CNC technique](image)

This research focused on studying the effect of using steel ring stiffeners around the web openings of a cellular beam. CLB4-R, the cellular beam reinforced by steel ring stiffeners, is shown in Figure 4.
Transverse slab reinforcement was provided for all specimens by installing Ø6 bars @ 100mm centres to achieve minimum reinforcement according to the ACI code. Shear studs (Ø19 x 60mm) were used as shear connectors to ensure full composite action.

Figures 5 and 6 and Table 1 show the geometrical characteristics of the experimental specimens.

| Symbol of beam | Overall depth | Opening diameter (Do) | Spacing (S) | Ring width (Br) | Ring thickness (Tr) |
|----------------|---------------|-----------------------|-------------|----------------|-------------------|
| Control        | 140mm         | NA                    | NA          | NA             | NA                |
| Non-composite  | 140mm         | NA                    | NA          | NA             | NA                |
| CLB1           | 173mm         | 100mm                 | 170mm       | NA             | NA                |
| CLB4-R         | 201mm         | 130mm                 | 170mm       | 37mm           | 5mm               |

![Figure 4: Installation of ring stiffeners](image1)

![Figure 5: Composite section details](image2)
Figure 6: Dimensions and details of tested specimens

Where:
D = overall depth of cellular beams.
D = parent, I section depth.
D₀ = opening diameter.
e = the clear space between two openings that follow one another.
S = center to center spacing between two openings.
Bᵣ = steel ring width.
Tᵣ = steel ring thickness.

2-2 Materials used

2-2-1 Concrete

The weights of concrete mix components were determined using ACI 211.1-91[7] for normal strength concrete with Ordinary Portland cement with properties corresponding to ASTM C150/C150M-19a
specifications [8], coarse aggregate of crushed gravel with maximum size of aggregate 14mm, and fine aggregate of natural sand with rounded shape and smooth grains compatible with ASTM C33/C33M-18 [9]. Sika ViscoCrete-5930 superplasticiser was used to reduce the water content and improve workability. To check the required compressive strength and slump, several trial mixes were tested in the structures laboratory of the Faculty of Engineering at the University of Kufa. Table 2 shows the final concrete mixture component weights used in this paper.

**Table 2: Weights of concrete mixture components**

| Mix No.                  | O.P. Cement (kg/m³) | Natural sand (kg/m³) | Crushed gravel (kg/m³) | Sika ViscoCrete (L/m³) | W/C |
|--------------------------|---------------------|----------------------|------------------------|------------------------|-----|
| Normal Strength Concrete | 300                 | 868                  | 1075                   | 1                      | 0.45|

Nine cylinders were tested to assess compressive strength according to ASTM C39/39M-18 [10]. The test for splitting tensile strength was done for six cylinders according to ASTM C496/496M-17 [11]. Table 3 below shows the results of laboratory tests of hardened concrete samples.

**Table 3: The test results of hardened concrete**

| Compressive Strength ($f'_c$) MPa | Splitting Tensile ($ft$) MPa |
|-----------------------------------|-----------------------------|
| Group 1                           | 40.3                        |
| Group 2                           | 37.52                       |
| Group 3                           | 39                          |
| Average = 38.94 MPa               | Average = 2.546 MPa         |

2-2-2 Steel

A tensile test was carried out on a standard coupon specimen according to ASTM A370 [6], giving yield and ultimate stresses of $F_y = 324$MPa and $F_u = 495$MPa, respectively. The elastic modulus and Poisson ratio were taken as $E = 200$GPa and 0.3, respectively.

2-2-3 Shear Connectors

Grade 4.6 studs of 19mm diameter and 60mm length, compatible with ASTM F593-17, were used. The studs were welded to the top flange of the steel section in a single line along the middle of flange width, using an AS B-248 electrode (400 x 350 mm) conforming to the specification of AWS-A5.1: E7018 [12]. The weld was done annularly on the circumference of the stud, achieving a uniform thickness of 9 mm, then the slag was cleaned by mechanical brush (see Figure 7).
2-3 Testing Procedure

In this study, all specimens were strengthening by placing transverse stiffeners under the applied load and support positions to prevent local buckling in the web due to the effect of the point loads. The specimens were positioned in the test machine taking care to ensure that they were in the correct position and that the beam's midspan was aligned with the centreline of the hydraulic jack, as illustrated in Figure 8. All specimens were tested under simple support settings with a two-point load.

LVDT sensors were installed at midspan with dial gauges at the same position – for calibration and confirmation – to measure deflections. A digital vernier caliper was used to measure the slip between concrete slab and steel beam at the ultimate load, and a crack meter was used to estimate the development of the crack width.

The load was applied using a load machine of 1000kN capacity that was connected with a data logger to record the load and deflection value. The test was executed at Engineering College Laboratories at the University of Kufa.

Figure 7: Welding of shear studs

Figure 8: Test procedure
3- EXPERIMENTAL RESULTS

The experimental results that will be explained in the next paragraphs include the failure mode yield load, ultimate load, and load against midspan deflection curves. These values will be used to assess the structural behavior of composite steel–concrete beams using cellular beams with and without strengthening by steel ring stiffeners around the openings. The results will be compared with the parent section to indicate if there is a benefit in the fabrication procedure.

3-1 Control Beam Results

The composite steel–concrete beam using an IPE140 parent beam was the first specimen tested in this study, and it was used as a control beam against which to compare the results of specimens using cellular beams with and without ring stiffeners. This specimen failed due to the steel yielding, as shown in Figure 9. The yield load was recorded as 120kN at a deflection of 7mm, and the ultimate load was 190kN at a deflection 29.2mm.

Figure 9: Failure mode in control beam

3-2 Non-Composite Beam Results

This beam was fabricated without shear connectors. The purpose of this beam was to study the effect of using shear connectors on the structural behavior and ultimate load of composite beams. This specimen failed due to the steel yielding, as shown in Figure 10. The yield load was recorded as 40kN at a deflection of 2.5mm, and the ultimate load of 135kN, at deflection 25mm, was 29% less than the ultimate load measured for the control sample (which had shear connectors).
Figure 10: Failure mode in non-composite beam

3.3 Specimen CLB1 Results

Specimen CLB-1 failed due to the formation of web-post buckling. The first indication of this failure mode appeared with the load at 145kN and midspan deflection at 6.8mm, and the web-post remained outside of the web plane until reaching failure load of 200kN, with midspan deflection of 29.8mm. The ultimate load for this beam was 5.3% greater than that of the parent beam. Figure 11 illustrates the web-post buckling mechanism. A horizontal shear force, $V_h$, acts along the welded joint of the web-post, resulting in a tensile stress region along the opening edges, AB and DG, and a compression zone at edges CD and BE. The parts of the web that are in compression tend to move away from the longitudinal axis of the web plane, while the tensile stress zones stay in place. This contrast in stress distribution makes the web-post fail with a distortion shape twisted like a propeller.

Figure 11: Web-post buckling mechanism

The deformation of CLB1 after the test is shown in Figure 12.
3-4 Specimen CLB4-R Results

Specimen CLB4-R failed due to the formation of plastic hinges at four points around the web opening. The first indication of yielding appeared with a load of 150kN and midspan deflection of 6.2mm, and the ultimate load was 225kN with a midspan deflection of 38.6mm. Thus, the ultimate load for CLB4-R was 18.43% higher than that measured for the parent beam. This test demonstrated the effects of using a steel ring to prevent web-post buckling. The failure mode of this beam is shown in Figure 13.

4- LOAD–DEFLECTION RESPONSE

Testing of the specimens allowed the identification of different behaviors that can be attributed to differences in the geometric properties of the specimens. The load–deflection curves were considered as a means of assessing the structural behavior. Figure 14 illustrates the load–deflection curves for all tested beams.
Figure 14: Load–deflection curves for all tested beams

The load–deflection curves can generally be divided into three stages: the linear stage, where there is a linear relationship between load and deflection; the elastic–plastic stage, where yielding commences in the specimen and deflection increases with only a small corresponding increment in load; and the plastic stage, typified by a large increase in deflection with a small load increment, indicating failure. This test demonstrated that a cellular beam performs better than a solid beam. This is because the increased depth of a cellular results in an increased moment of inertia, which has an inverse relationship with deflection. The cellular beam with strengthening performed better than the other beams because the stiffening transforms the section at the opening from a T-section to an I-section, as shown in Figure 16.

Table 4 summarizes the ultimate loads and allowable loads at maximum deflection L/360 measured for each beam.

| Beam          | Allowable Load at L/360 | Ultimate Load | Failure mode           |
|---------------|-------------------------|---------------|------------------------|
|               | Allowable Load (kN)     | Ultimate Load (kN) | Ratio of Ultimate Load (%) |
| Control       | 75                      | 190           | 100%                   |
| Non-Composite | 58                      | 135           | 71%                    |
| CLB1          | 112                     | 200           | 105.26%                |
| CLB4-R        | 133                     | 1225          | 118.43%                |
Deflection of composite steel–concrete beams is usually restricted to a certain maximum value. The International Building Code (IBC) [13] has set a limit of span/360 for service live load deflections. This deflection is given as the maximum deflection that ceiling joists can withstand without cracking the underlying plaster. Figure 15 shows the IBC allowable loads for all tested beams. The maximum deflection allowed for the 1700mm long specimen beams used in this study was 4.7mm.

Based on the IBC deflection criterion, the allowable load for the control specimen was 75kN. According to the experimental results, the allowable loads for the non-composite specimen and CLB1 and CLB4-R were 58kN, 112kN, and 133kN, respectively, as shown in Figures 17 and 18. The permitted load for Specimen CLB1 was 49.3% higher than that for the control specimen and 77.3% higher than the allowable load for beam CLB4-R.

![Figure 15: Allowable load at maximum deflection L/360 according to IBC](image)

5- EFFECT OF USING STEEL RING STIFFENERS

The test showed that the dominant failure mode for composite steel–concrete beams using cellular beams with large web openings was web-post buckling. This type of failure happened due to the effect of horizontal shear forces along the welding joint in the web-post, especially where there was a small clear distance between openings. Placing a steel ring stiffener inside the web opening is a means of transforming the section at the opening from a T-section to an I-section, as shown in Figure 16.

![Figure 16: Effect of steel ring on the behavior of cellular beams](image)
6- CONCLUSIONS

1) The results showed that the non-composite beam (without shear connectors) had an ultimate load 29% lower than that of the composite beam.
2) In terms of IBC deflection limits, the allowable load for the CLB4-R beam at maximum deflection L/360 was 77.3% more than the allowable load of the original beam.
3) The fabrication process to convert the solid beam to a cellular beam with an expansion depth ratio of 1.23 resulted in a 5.3% increase in the ultimate load without any additional material.
4) The dominant failure mode for the cellular beam with large web openings is web-post buckling, due to the effect of horizontal shear forces acting along the welded joint. The installation of steel ring strengthening prevented this type of failure; the subsequent failure mode was the Vierendeel mechanism.
5) The results showed that the use of steel ring stiffeners with geometrical properties $B_r = 37\text{mm}$ and $T_r = 5\text{mm}$ is a very effective solution to increase the load-carrying capacity by up to 18.43% more than that of the parent section. Installing the stiffeners resulted in an increase in weight of only about 10.6%.

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