Responsible Design and Delivery of the Constructed Project
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# BEHAVIOR OF FULLY ENCASED COLD FORMED STEEL JOISTS WITH/WITHOUT WEB OPENINGS: EXPERIMENTAL INVESTIGATION

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This paper presents an experimental investigation on the behavior of encased light cold-formed steel joists with/without web openings. The study is carried on two sets of composite beams constructed of cold-formed steel joists using I-beam built-up sections. The first set has no web openings while the second set has circular web openings. Each set consists of three beams with various steel section-concrete reinforcing ratio. The constant parameters included in this study are the cross sectional area of the specimen, distribution of web openings in the encased steel I- joist, and the compressive strength of concrete. The tests have been conducted by applying two concentrated identical loads. Consequently, a comparative study is carried out to compare between the behavior of specimens within one set, and a comparison between the specimens of the two sets. This comparison is related to strength, stiffness, ductility, energy absorption capacity and failure modes. Based on the testing results, it is concluded that, the load capacity of the composite beams without web openings is greater than that with web openings for the same steel ratio. But the existence of web openings in the encased steel joists enhances the ductility and the energy absorption of the composite beams. Also using cold formed steel I-joists in the composite beams allow the failure mode to be ductile flexural failure.

*Keywords:* Composite beam, Stiffness, Energy absorption capacity, Failure mode, Web openings, Experimental study.

## 1 INTRODUCTION

Cold-formed steel (CFS) is the common term for products made by rolling or pressing thin gauges of steel sheets into goods. There are many ways to create cold-formed steel section. One way to deform the sheet into a usable product includes working sheet steel using folding, rolling, or presses (Yu and Wiley 2000).

Some of the main properties that make cold-formed steel more preferable are (Hancock *et al.* 2001, Dandens *et al.* 2011) lightness in weight, ease of prefabrication and mass production, fast and easy erection and installation, economic transportation and handling, and recyclable material.

Composite construction achieves important benefits by making steel and concrete work together. These advantages may be improved by using light cold formed steel sections. Light sections have been introduced in the composite construction and the general principles of composite design using light steel sections are the following:

- During construction, light steel beams are designed elastically to support the construction loads.

- Once the steel and concrete are acting compositely, composite light steel beams are designed plastically to support the loads acting at the ultimate limit state (Hamidi 2013).

Wehbe *et al.* (2013) carried out a series of experimental studies on full-scale test specimens representing concrete/CFS flexural elements under gravity loads. These studies were designed to investigate the structural performance of concrete/CFS simple beams.

## 2 AIM AND OBJECTIVES

The primary goal of the research was to conduct an experimental investigation of the encased composite beams with and without web openings and compare them to each other. The reason of using web openings is to replace the stand-off screw done by the previous investigation. The tests were conducted by applying two concentrated identical loads, each load is acting at a distance 250 mm from the mid-span on each composite beam. Specific objectives of the test program to this report are to:

(i) Investigate the effectiveness of using the web openings.
(ii) Observe the mode of flexure behavior.
(iii) Figure out if the composite beam is behaving as one unit.

## 3 EXPERIMENTAL INVESTIGATION

### 3.1 Test Specimens

Six full-scale rectangular composite beams were constructed and tested in this study. All the beams have a 3000 mm clear span and a rectangular section of 300 x 200 mm, reinforced by cold formed steel plates (Top flange, Bottom flange, Web) welded together to form the steel I-joist (built-up section) encased in the concrete to form a new concept of composite beam.

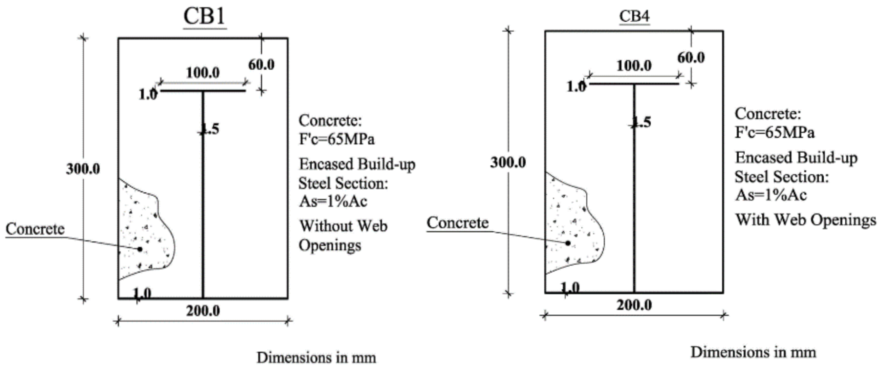


Figure 1. Typical cross-sections of the composite beams with/without web openings.

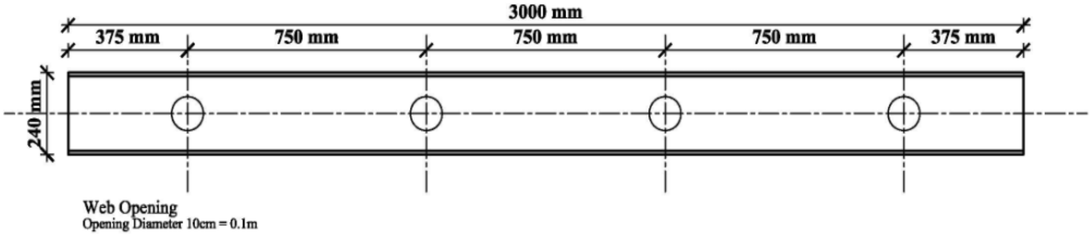


Figure 2. Side view for the steel I-joist with web openings (set 2).

Table 1. Characteristics of the experimental test specimens.

| **Sample** | **CB1** | **CB2** | **CB3** | **CB4** | **CB5** | **CB6** |
|---|---|---|---|---|---|---|
| **Percentage of steel (%)** | 1% | 2% | 3% | 1% | 2% | 3% |
| **Width of beam (b) (mm)** | 200 | 200 | 200 | 200 | 200 | 200 |
| **Depth of beam (d) (mm)** | 300 | 300 | 300 | 300 | 300 | 300 |
| **Width of top flange (mm)** | 100 | 100 | 100 | 100 | 100 | 100 |
| **Thickness of top flange (mm)** | 1 | 2.5 | 4 | 1 | 2.5 | 4 |
| **Width of bottom flange (mm)** | 200 | 200 | 200 | 200 | 200 | 200 |
| **Thickness of bottom flange (mm)** | 1 | 2.5 | 4 | 1 | 2.5 | 4 |
| **Height of the web (mm)** | 238 | 235 | 232 | 238 | 235 | 232 |
| **Thickness of the web (mm)** | 1.5 | 2 | 3 | 1.5 | 2 | 3 |
| **Number of web openings** | NA | NA | NA | 4 | 4 | 4 |
| **Diameter of web openings (mm)** | NA | NA | NA | 100 | 100 | 100 |

Composite beams were divided into two sets (Table 1, Figures 1 and 2). Set 1 contains beams CB1, CB2 and CB3 without web openings. Set 2 contains beams CB4, CB5 and CB6 with web openings, see Figure 2 for locations of web openings (AISI Standard S201-07 2007).

## 3.2 Materials

Eleven standard cylinders of 152.5mm (6in) diameter x 305mm (12in) height were cast from each batch and kept in the same environment as the composite beams. The average compressive strength $f_c^{'}$ at the time of testing (after 28 days) was 65MPa (ASTM C39 (2000), Carreira and Chu 1985).

The steel plates used in the composite beam samples were also tested and showed a yield strength of 161.91 MPa and an average modulus of elasticity of 211048 MPa.

## 3.3 Test Setup and Instrumentation

The tests were carried out by increasing the pressure in the hydraulic jack and recording the central deflection of the composite beam at each increment of the load as shown in Figure 3.

Figure 3. Installation of the samples with the testing machine.

# 4 EXPERIMENTAL BEHAVIOR

All the specimens were tested after curing. The beams were subjected to flexural loads to study their behavior. The load deflection curve is then plotted online allowing monitoring of the behavior in the zone within elastic, plastic then damaged phase.

The load-deflection curves for composite beams CB1 and CB4 are shown in Figure 4.

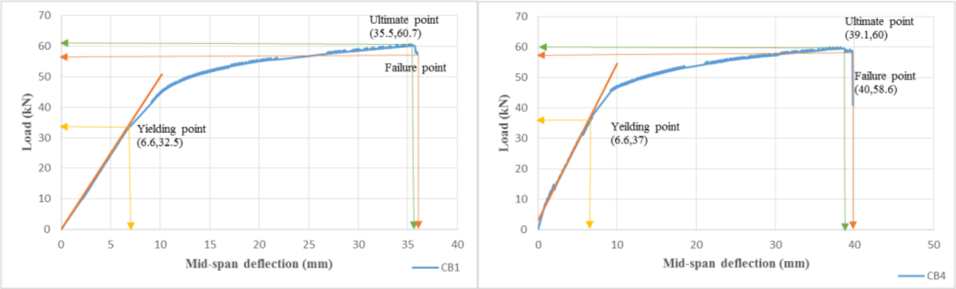


Figure 4. Typical Load-Deflection curves for the composite beams with/without web openings.

Table 2. The experimental results of the composite beams.

| Composite Beam | % of As | $P_y$ (kN) | $\Delta_y$ (mm) | $P_u$ (kN) | $\Delta_u$ (mm) | $P_f$ (kN) | $\Delta_f$ (mm) | $\Delta_f/\Delta_y$ |
|---|---|---|---|---|---|---|---|---|
| CB1 | 1% | 32.5 | 6.6 | 60.7 | 35.5 | 57.4 | 36 | 5.45 |
| CB2 | 2% | 87 | 7.35 | 127 | 24 | 113 | 26.4 | 3.5 |
| CB3 | 3% | 98 | 9 | 137 | 16.5 | 133 | 16.5 | 1.83 |
| CB4 | 1% | 37 | 6.6 | 60 | 39.1 | 58.6 | 40.5 | 6 |
| CB5 | 2% | 60 | 9 | 95.6 | 31.6 | 71.2 | 32.6 | 3.56 |
| CB6 | 3% | 82 | 8.87 | 97.9 | 17.8 | 86.7 | 23.5 | 2.72 |

## 5 DISCUSSION AND COMPARISON OF THE EXPERIMENTAL RESULTS

### 5.1 Load-Deflection Behavior

The beams will be compared according to stiffness, load-deflection, ductility, energy dissipation and failure modes. The load-deflection curves of the composite beams with and without web openings for different steel ratios are shown in Figure 5.

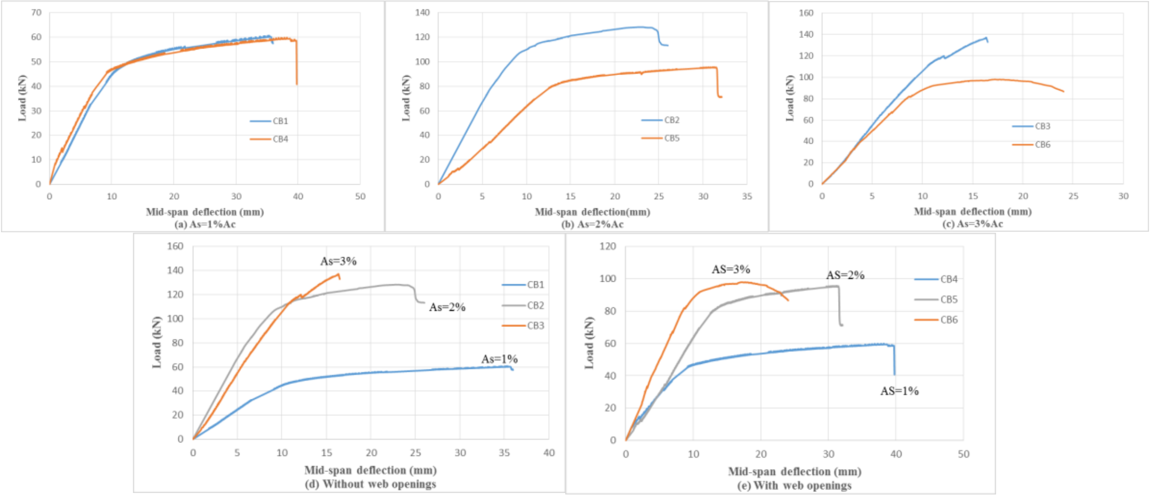


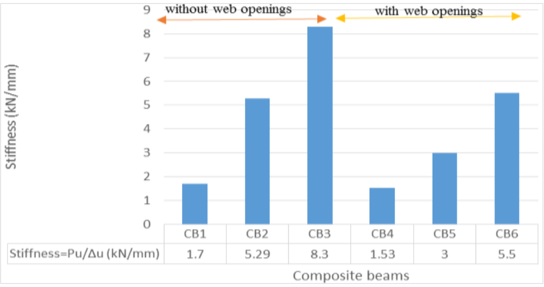
Figure 5. Load-deflection curves for the tested composite beams.

### 5.2 Stiffness

Stiffness is defined as the load required causing unit deflection. The stiffness values of the specimens at ultimate loads are shown in Figure 6.

## 5.3 Ductility

The ratio of the failure deflection to the deflection at first yield is known as ductility factor (μ). Figure 7 represents the ductility factor of the tested composite beams.



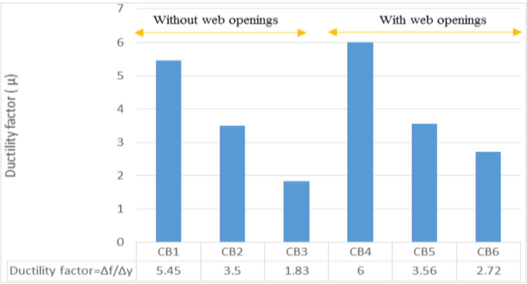


Figure 6. Stiffness values.

Figure 7. Ductility factor.

## 5.4 Energy Absorption Capacity

Energy absorption capacity of the beam members can be approximated as the area under the load-deflection curve. Figure 8 shows the energy absorption capacities of the tested composite beams.

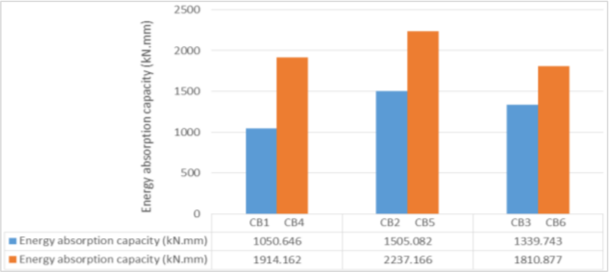


Figure 8. Energy absorption capacity.

## 5.5 Failure Modes

The cracks were formed in the center of the samples and originated from the top (tension zone) of the specimen and extended towards the bottom (compression zone) of the specimen. The majority of cracks are formed near the zone of the points loading. As the load increases, the initial cracks have widened till the ductile flexural failure occurred (plastic zone) in all the composite beams with or without web openings in the encased steel beam.

# 6 CONCLUSIONS

Six specimens were designed, fabricated and tested to investigate the flexural failure and the behavior of the composite beams with cold formed steel I-joist encased in concrete, with different percentages of steel-concrete reinforcing ratio, with or without web openings.

The ultimate strength, load-deflection curve, ductility, stiffness, energy absorption capacity and the failure mode of each specimen were recorded and studied carefully.

The major results obtained from this study are summarized as follows:

(i) The ultimate load capacity of composite beam without web openings and with steel ratio 3% (CB3) increases by 125.7% and 7.9% more than CB1 having steel ratio 1% and CB2 having steel ratio 2% respectively and the ultimate load capacity of CB2 increases by 109.2% more than CB1. While the ultimate load capacity of composite beam with web openings and with steel ratio 3% (CB6) increases by 63.2% and 2.4% more than CB4 having steel ratio 1% and CB5 having steel ratio 2% respectively, and the ultimate load capacity of CB5 increases by 59.3% more than CB4. Thus, the ultimate load capacity of the composite beams increases as the percentage of steel increases.

(ii) The ultimate load capacity of composite beams without web openings with steel ratio 1% (CB1), 2% (CB2) and 3% (CB6) increases by 1.2%, 32.8% and 40% more than composite beams with web openings with steel ratio 1% (CB4), 2% (CB5) and 3% (CB6) respectively. It can be concluded that the load capacity of the composite beams without web openings is greater than that with web openings for the same steel ratio.

(iii) Stiffness values of the specimens without web openings are higher than that with web openings approximately by 11.11%, 76.33%, and 50.9% for steel ratios of (1%, 2%, and 3%) respectively, means that the stiffness increases as the percentage of steel increases.

(iv) Web openings improve the ductility of the composite beams of the same steel ratio. Also, it shows that the ductility of the samples with and without web openings decreases as the steel ratio of the encased steel beam increases.

(v) Specimen with/without web openings have the same capacity at 1% of steel (lower ratio).

(vi) The energy absorption capacity for the composite beams with web openings is higher than that for the composite beams without web openings for all steel ratios 1%, 2% and 3%, means that the introducing of web openings in the composite beam enhances its energy absorption capacity.

(vii) Using Cold formed steel I-joist (built-up section) in the composite beams allow the failure mode to be ductile flexural failure.

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