Flexural behavior of composite open web steel joist and concrete slab

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Abstract. Experimental research has been carried out to study the behavior of composite open web steel joists under monotonic loading. Four composite joists were fabricated with two types of web members and span-to-depth ratios were tested. The concrete slab 400 mm wide, and 90 mm overall depth overlaid on a corrugated steel sheet. The composite system was simply supported over 3000 mm span and subjected to a uniformly distributed loading. Test results are presented in terms of slip between composite slab and the top chord of steel joist, load-deflection, and load-strain relations. Based on the experimental results, it can be concluded that lowering span/depth ratio has a significant effect on failure pattern with increase in ultimate capacity about 8%. Additionally, the results show that using double angles web type has only a little influence on deflection but increased ultimate capacity about 10% over similar composite joist with rounded bars web.

1. Introduction
Steel-concrete composite beams have been recognized as one of the most economical structural system for multi-storey buildings and bridges. A good example of composite construction is composite open web steel joist, which comprises an open-web steel joist and a cast-in-place composite concrete slab. The benefit of open web configuration permits an easy accommodation for service systems like ducts, and pipes. In addition, using steel sheets as a permanent formwork results in speedy construction compared with conventional composite beams. To ensure that the composite steel-concrete system acts as a single unit, shear connectors are attached to the steel top chord and embedded in the concrete slab. Composite open web steel joist is designed as simply supported beam and its ends are either bolted or welded to the supporting beam or joist girder.

In 1965, the first testing of composite open web steel joists was carried out by Lembeck [1]; followed by Wang and Kaley in 1967 [2]. The composite action was achieved by extending the web members above the top chord angles into the concrete slab. Cold-formed hat-shaped sections were used to construct the top and bottom chords. The experimental results of composite steel joists showed that there was about 20 percent reduction in deflection, and an increase approximately 14 percent in ultimate moment than that of the tested conventional joists. Also, it was found that Robinson and Fahmy (1978) [3] tested a number of composite joists with metal steel deck. The results showed that the strength and stiffness of composite joists were greater than non-composite joists. Gibbings et al. (1991) [4] tested eight composite joists with spans ranging from 40 ft. to 56 ft. and depths from 14 in. to 36 in. The concrete slabs were casted from normal concrete. Headed studs with ¾ in. diameter were used as shear connectors. The researches verified the assumption of neglecting any contribution of top chord in computing the ultimate strength design method of the tested joists.
Four simply supported composite open web steel joists were examined under static loading to investigate the effect of web member type and span/depth ratio on the structural performance of these joists. The ultimate capacity, deflection, strain profile, and mode of failure were presented and discussed. It is worth to mention that this study provides a basis for the experimental research of the behavior of this type of light weight structures which are commonly used in Iraq, considering various types of loading and using modern types of concrete.

2. Materials

2.1 Concrete
Normal strength concrete cylinders were cast from the same batch of concrete, and were performed on the days of composite joist tests to determine the compressive strength in accordance to ASTM C39/C39M – 14 [5]. Ordinary Portland cement conforming to the Iraqi Specification No.5/1984 [6] was used. Sand falling to Zone II was used as Fine aggregate, and 12.5 mm maximum size coarse aggregate was used for the concrete mix. The aggregates were complied with the Iraqi Specification No.45/1984 [7].

2.2 Steel
Three tensile coupons were extracted from each component of the steel joist in accordance with ASTM 370 specification [8]. The main values of test results as yield stress and ultimate stress are shown in table 1. Figure 1 shows the coupons of steel specimens during tensile test.

| Component               | Dimensions (mm) | Yield Stress (MPa) | Ultimate Stress (MPa) |
|-------------------------|-----------------|--------------------|-----------------------|
| Top Chord               | L 50X50X5       | 371.66             | 601.66                |
| Bottom Chord            | L 76X76X5       | 326.66             | 546.66                |
| Web Members             | L 40X40X5       | 281.66             | 423.33                |
| Welded Wire Mesh        | Ø 6             | 543                | 568.22                |
| Headed Shear Connector  | Ø 16            | 425                | 581.33                |

3. Description of Test Specimens
Experimental investigation on the behavior of four simply supported composite open web steel joists was conducted. All joists had a constant span of (3m) and designed with two kinds of span-to-depth ratio, 13.5 or 15.5.
The specimens were fabricated using 2L 50X50X5 mm and 2L 76X76X5 mm back-to-back double angles for the top and bottom chords, respectively. Two different types of web members were used, solid 25 mm in diameter plain rounded bars and 2L40x40x5 mm double angles. Description and details of the composite joist specimens are presented in table 2 and figure 2.

A total of 28 double row shear connectors with 16 mm diameter and 75 mm length after welding were placed in the strong position. The number of shear connectors is designed as per Steel Joist institute SJI, 2015 [9] for all specimens so that it exceeds the tensile force of the bottom chord to ensure ductile failure. Plywood boards with inner dimensions of 400 mm width and total of 90 mm depth were placed before pouring of concrete. Then, normal concrete was cast on the top of profiled steel sheet and already placed welded wire fabric of 6 mm bars. Burlap sheeting was used to cover the concrete slab for moist curing for 28 days. Figure 3 shows the profiled steel sheet with the welded wire mesh, casting, and curing of the concrete slab.

Table 2. Description and details of tested specimens

| Specimen  | Span Length (m) | Depth (mm) | Concrete Compressive Strength (MPa) | Flexural Strength, (MPa) | Splitting Tensile Strength, (MPa) | Web Type (mm) |
|-----------|----------------|------------|------------------------------------|--------------------------|-----------------------------------|--------------|
| N13.5ROM  | 3              | 222        | 43.65                              | 7.60                     | 4.87                              | Rounded bars Ø 25 |
| N15.5ROM  | 3              | 193        | 42.51                              | 7.12                     | 4.62                              | Rounded bars Ø 25 |
| N13.5DOM  | 3              | 222        | 45.82                              | 6.67                     | 4.92                              | 2L40x40x5     |
| N15.5DOM  | 3              | 193        | 42.41                              | 6.17                     | 4.12                              | 2L40x40x5     |

Figure 2. Typical sample details. (a) Typical (N13.5ROM and N15.5ROM) joist samples. (b) Typical (N13.5DOM and N15.5DOM) joist samples.
Figure 3. Composite slab construction stages. (a) Placement of welded wire mesh. (b) Concrete poured. (c) Specimens curing.

4. Loading Scheme, Description and Measurements

A typical instrumentation arrangement was used for each specimen. Eight strain gauges were used to measure the strain of the steel joist with one strain gauge placed on the concrete slab, resulting in a total of nine strain gauges per joist, as shown in figure 4. Vertical deflection was measured at the centerline of the composite joist using a linear variable differential transducer (LVDT). In addition, relative slip measurement of the concrete slab was made using another LVDT attached to the steel joist top chord. A data acquisition system connected to a computer was used to collect the data from the strain gauges and the LVDTs.

The load procedure was similar for all tests. The load was applied using a single hydraulic ram and distributed by three-tiers of 250x250 mm I-beam to the concrete slab, see figure 5, to simulate a uniformly distributed force pattern. To stabilize the composite joist specimen, an initial load equal to 10 percent of the calculated strength was applied. Then, all the instrumentations were re-initialized and load increments of 1 kN were applied until failure. Figure 6 presents the composite joist specimen under load and the data acquisition system that used was in this experiment.

Figure 4. Instruments positions detail of the composite joist.
Figure 5. Loading arrangement for composite joist specimens (all dimensions in mm).

Figure 6. Composite joist specimen setup.

5. Result and Discussion
As mentioned previously, the main objective of this paper was to investigate the structural behavior of composite joists with two types of web members and span-to-depth ratios. The results of experimental work consist of load-deflection at midspan response, crack pattern, load-slip at interface between the concrete slab and the top chord, and strain behavior were presented herein.

5.1 Load-deflection Behavior
Table 3 shows the ultimate force, maximum mid-span deflection for all tested specimens. In figure 7, specimen **N13.5DOM**, exhibited an increase in stiffness compared to the other specimens, which showed a similar behavior until the ultimate failure of the joists. It also appears that the measured
deflection at midspan at ultimate load of specimen **N15.5ROM** was slightly more than the deflection of other three tested specimens.

### Table 3. Experimental test results

| Specimen  | $P_{u}$ (kN) | $\Delta_{\text{mid-span}}$ (mm) | $P_{u}/P_{u(N13.5ROM)}$ |
|-----------|---------------|---------------------------------|--------------------------|
| N13.5ROM  | 500           | 23.69                           | 1                        |
| N15.5ROM  | 540           | 27.58                           | 1.08                     |
| N13.5DOM  | 550           | 24.80                           | 1.1                      |
| N15.5DOM  | 570           | 25.91                           | 1.14                     |

#### Figure 7. Load–deflection curves of the tested specimens.

### 5.2 Crack Pattern and Failure Modes

During the tests, the cracks in the concrete slabs near the support started at approximately 60% and 54% of the ultimate load in specimens **N13.5ROM** and **N13.5DOM**, respectively. Delamination between the concrete slab and the profiled sheet was observed at 460 kN near to the supports for both specimens **N13.5ROM** and **N13.5DOM**. For specimens **N15.5ROM** and **N15.5DOM**, cracks in concrete slabs near midspan started under relatively small loads (approximately 31% and 38%), while delamination between the concrete slab and the profiled sheet was marked at 330 kN and 400 kN, respectively. Photographs of the crack patterns at failure stage of all tested composite joists are presented in figure 8. It can be noticed that the cracks occurred mostly within the shear span for specimens **N13.5ROM** and **N13.5DOM**, whereas the cracks for specimens **N15.5ROM** and **N15.5DOM** were observed close to the midspan. However, it can be remarked that all the composite joists have exhibited significant composite action during the test without any failure in shear studs.
5.3 Strain Behavior and Neutral Axis of the composite joists

Strain gauges were placed at various locations to examine the strain behavior of the composite joists. Figure 9 depicts the load-strain relationship for the tested specimens. Based on these results, one can conclude that the neutral axis for all specimens are located within the top chord of the steel joist, which are about 217 mm for specimens N13.5ROM and N13.5DOM, and 168 mm for specimens N15.5ROM and N15.5DOM from the bottom chord of the steel joist. That means all the steel joists are subjected to only tensile forces and there is no compression buckling, as recommended by SJI [9]. Except for specimen N13.5ROM there was a slight local bucking at the first compression diagonal web member occurred before reaching the ultimate load. Also, it is noticeable that the strain behavior of the bottom chord of the composite joists were similar, except for strain gauge (S7) in N13.5DOM composite joist. The load-strain behavior for this strain gauge was approximately linear because it was located at interaction of two web members.
5.4 Load-Slip Behavior

Because of using two different types of material, steel joist and concrete slab, the relative slip at the interface layer should be checked. LVDT sensor was attached to the top chord of the steel joist to record the relative movement values with the concrete slab. The slip behavior of all tested joists is shown in figure 10, where each figure presents the load versus slip for two specimens. The percentage of decrease in slip, with respect to \textbf{N13.5ROM}, is 10\% for composite joist \textbf{N15.5ROM}. While the increase in slip percentage is equal to 65\% for composite joist \textbf{N13.5DOM} at the ultimate load. In addition, it can be noticed that the specimen \textbf{N15.5DOM} has the greater slip value compared with the other three specimens.

Figure 9. Strain Profile for Tested Composite Joists.
6. Conclusion
This study investigates the behavior of uniformly loaded simply supported composite joists. Based on the experimental results reported in this paper, the following conclusions can be made:
1- All the tested composite joists failed in bottom chord yielding and concrete crushing without any failure in the shear connectors.
2- The ultimate strength of composite joists with double angle web member increased by 1.8 -14%, as compared to composite joists with rounded bar web. Also, it can be mentioned that the composite joists reached their ultimate strengths without buckling in either types of web members.
3- Decreasing the span-to-depth ratio leads to increase the concrete cracks, and deflection values from 4.4–16.4%. Two failure modes were observed in the tests: the specimens with span/depth ratio of 13.5 failed in shear, while specimens with lower span/depth ratio, equal to 15.5, failed in flexure.
4- Full composite action was observed until yielding for all tested joists, as expected, since the number of studs exceed the steel bottom chord yielding force, which is compatible with the design recommendation of Steel Joist institute SJI, 2015 [9].

References
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