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# A Study on the Behavior of Composite Concrete and Open Web Steel Joists

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K E Y W O R D S

Composite open web joists, Push-out test, Headed studs, Shear connection degree

A B S T R A C T

*In this research, the results of three composite open web steel joist static tests are presented along with the results of companion pushout tests. The effect of shear connection degree and span-to-depth ratio on the behavior of composite open web joists under distributed static loading is reviewed and discussed, followed by a comparison of results of the shear stud strength from push-out tests, back-calculated from the ultimate capacity of the composite joist tests, and to the provisions in the AISC, EC4, NZS, SJI, and BS5950. Specimen test results of the studied span-to-depth ratios showed that the load-deflection behavior was similar to ultimate capacity difference less than 10%, but they experienced different failure modes and deflection. And when the test results were compared based on the shear connection degree, they revealed that the composite open web joist designed with partial shear connection suffered from severe deformation and deflection accompanied with higher ultimate capacity.*

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## 1. Introduction

Composite construction incorporates a steel member and concrete slab with mechanical joining to ensure they act as an integral unit. This results in a reduction in the deflection and increases the stiffness, which offers shallower members and free column space compared with non-composite construction. Composite open web steel joists have been used for some years in-floor systems, and there was a significant cost saving was achieved compared to a rolled steel girder and pre-stressed concrete girder construction [1]. The term composite open web steel joist refers to parallel top and bottom chords, open web, and concrete slab laid on a profiled steel sheet. The open web configuration allows service conduits to pass through without increasing in building height. Suitable shear connectors between the concrete slab and the steel top chord are used to avoid longitudinal slip at

their interface. Headed studs are the most common shear connectors which welded to the top chord of the steel joist.
Many previous researches on headed studs with profiled steel decking using push-out tests as well as composite joists tests were performed. For example, Robinson [2] investigated the influence of the profiled sheet on the strength of the composite beam. The test performed on full-scale beams and push-out tests. Robinson concluded that the shear connector contributed to the beam maintaining load after the onset of concrete cracking, and the rib height-to-width ratio was an important factor affected the concrete crack.
Placement of studs in the strong (favorable) or weak (unfavorable) position of the rib flute, see Figure 1, was investigated by Mottram and Johnson [3]. They developed equations that take into consideration rib and stud geometry, and the amount of concrete on the front side of the stud. Based on many experimental push-out tests, Bonilla et al. [4] conducted a finite element study to determine the resistance of the headed studs in the composite beams with a profiled sheet. They reported that the stud position has to be taken into consideration in shear resistance calculation and increasing the thickness of the steel profiled sheet results in enhancing the shear resistance when headed studs are placed in the weak location.
Yanez et al. [5] experimentally calculated the stud anchor stiffness coefficients when the stud is placed in the weak or strong location in a modified push-out test, and related to predicting overall deflection of the composite steel joist system. They found that the studs placed in a strong position in the profiled sheet enhanced deflection by 5% as compared to the weak position. Also, Ding et al. [6] investigated, through experimental and finite element modeling, the effect of stud diameter, stud yield strength, concrete strength, and length/diameter ratio of the stud on the shear capacity of the push-off test. The results demonstrate that the ultimate shear capacity increased with stud diameter and yield strength, while the length/diameter ratio has no noticeable effect on it.
Hadeed et al. [7] tested seven composite joists with many variables included concrete type and distribution of shear connectors. Also, the author used an over- and under-connected parameter effect of Ø 10 x 30 mm length welded headed studs distributed along with double angles of 2L31.5x31.5x3 mm top chord. The test results showed that the composite joist with an under-connected shear connection degree exhibited 84% of the over-connected control one.
The objective of this paper is to study the strength and behavior of composite open steel joists fabricated with different degrees of shear connection and the effect of the span-to-depth ratio of steel joists on the performance of composite open steel joists. Also, an analysis was made to compare the strength obtained experimentally of the shear studs from push-out tests with that as per the AISC 360-16 [8], EC-4 [9], NZS 3404.1[10], Steel Joist institute SJI [11], BS5950-3.1 [12] specification provision, and a back-calculation for the values of stud strengths from composite joist tests was also presented. It is worth to mention that the push-out and composite open web joist test specimens were part of a research project conducted to investigate the effect of different test parameters as the type of the applied loading, web members, and concrete on the performance of the composite open web steel joists.

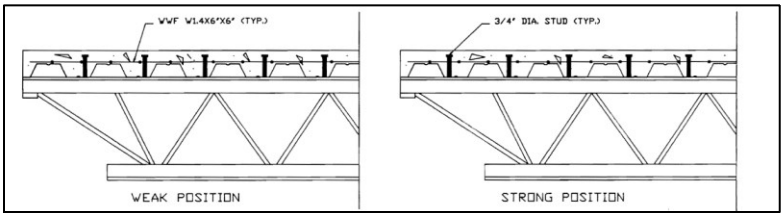



**Figure 1: Stud positions [9].**

## 2. Experimental Program

*I. Composite open web joists specimens*

*1. Composite open web joists Description*

Each specimen consisted of a concrete deck slab and steel open web joist. The steel joist is constructed from double angles 2L50X50X5 mm and 2L76X76X5 mm welded back-to-back for top and bottom chords, respectively. The dimensions of composite concrete deck slab are 400mm width, 3000 mm length, and 90 mm total thickness, and reinforced with a single layer of mesh wire of size 6 mm diameter and spaced 150mm c/c in both directions. The over-connected composite joist contains

14 headed stud shear connectors per half span uniformly distributed along the longitudinal axis of each steel joist. Two-headed studs were placed in a row in a strong position per steel deck rib to satisfy over-connected shear connection, while the under-connected one contains seven-headed studs only, which alternately placed on each top chord angle, as shown in Figure 2. The overall length of the headed studs was 75 mm, after welding, and diameter 16 mm were used to construct both test specimens. All slabs were cast with normal concrete strength, and companion standard cylinders for determination of compressive strength of these slabs were cast and tested. The summary of specimens' details is presented in Table 1 and Figure 3, respectively. Additionally, the values of the compressive strength of the concrete of each specimen are listed.

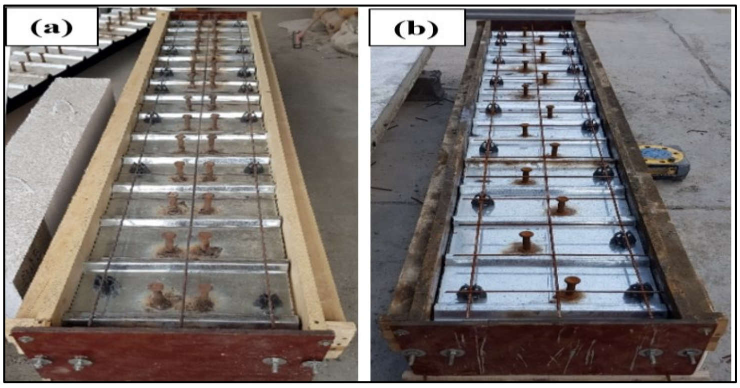



**Figure 2: (a) Over- and (b) Under-connected composite open web steel joists.**

*2.Composite Open Web Joists Instruments and Testing Procedure*

All specimens had the same instruments arrangements for deflection, strain, and slip measurements. All of these instruments were monitored using a data acquisition system to collect data. A total of five strain gauges per specimen were located at different positions, as shown in Figure 4. Four gauges were placed at the steel joist and one strain gauge was placed at the top face of the composite deck slab. The maximum deflection of the composite open web joist was monitored through LVDT placed at the midspan.

**Table 1: Summary of composite open web joists specimens' details.**

| Specimen | Span Length (m) | Steel Joist Depth (mm) | Concrete Strength (MPa) | Shear Connection Per Half Span |
|---|---|---|---|---|
| N13.5ROM | 3 | 222 | 43.65 | 14 |
| N15.5ROM | 3 | 193 | 42.51 | 14 |
| N13.5RUM | 3 | 222 | 42.98 | 7 |

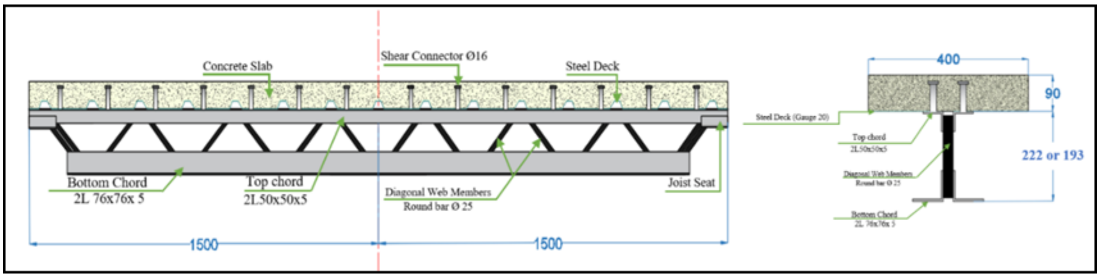



**Figure 3: Schematic drawing of the composite open web joists specimens (All dimension in mm).**

A single hydraulic ram was distributed to a third-tier distribution system, as shown in Figure 5. The load program was identical for all tests by applying 10% of the calculated strength, then the load was removed and the instruments were re- initialized to stabilize the specimen. After that, the load was applied in increments of 1 kN.

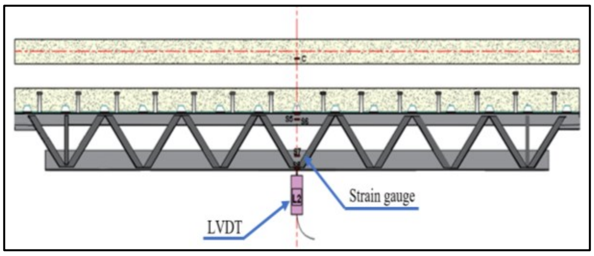



**Figure 4: Instruments positions detail of in the composite joist.**

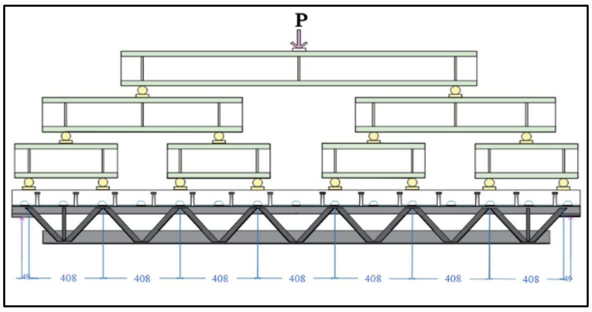
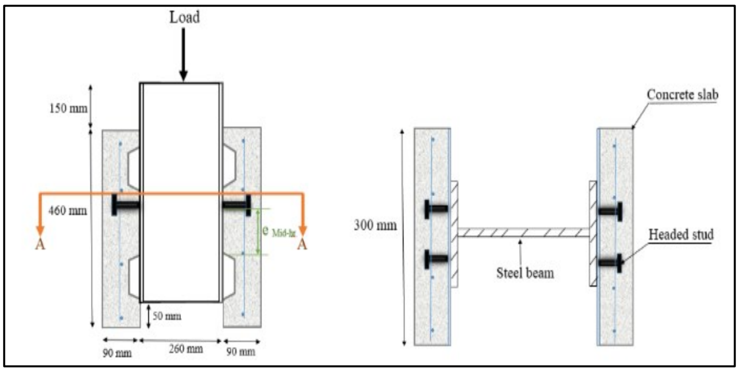



**Figure 5: Loading arrangement for composite joist specimens (All dimensions in mm).**

*II. Push-out test specimens*

*1. Push-out Test Specimens Description*

The push-out specimens were fabricated using the same profile steel sheet and shear stud height that used in the composite joist specimens. Generally, the specimens comprised of steel I beam, and two identical concrete slabs attached to the beam flange. In this experiment, the push-out specimens constructed according to BS 5400-5:2005 standard [13]. The steel section was 254x146x43 UB beam. A normal concrete slab, 90 mm thick by 300 mm wide by 460 mm, was cast on the deck, which was perpendicular to the steel beam. Two shear connectors were welded with 16 mm diameter and 75 mm length in the strong position. A single layer welded wire fabric WWF 6x6 mm diameter with 150 mm c/c in each direction, was placed before concrete casting. Concrete test cylinders 150 X 300 mm were cast from the same batch of concrete of push-out specimens. Figure 6 shows a schematic drawing of the push-out specimens.




(a) (b)

**Figure 6: Push-out Specimens (a) Front View (b) Plan View.**

*2. Push-out Test Specimens Instruments and Testing Procedure*

The slip between the concrete slab and the steel section was measured using two LVDTs mounted at the same level of studs on each slab. The specimens were subjected to monotonic loading with a single hydraulic ram. The test was carried out until failure with load increments equal to 1 kN. Figure 7 illustrates the push-out test setup.

**3. Materials Mechanical Properties**

The concrete cylinders' test was performed to determine the compressive strength of the concrete used in both push-out and composite joist specimens.

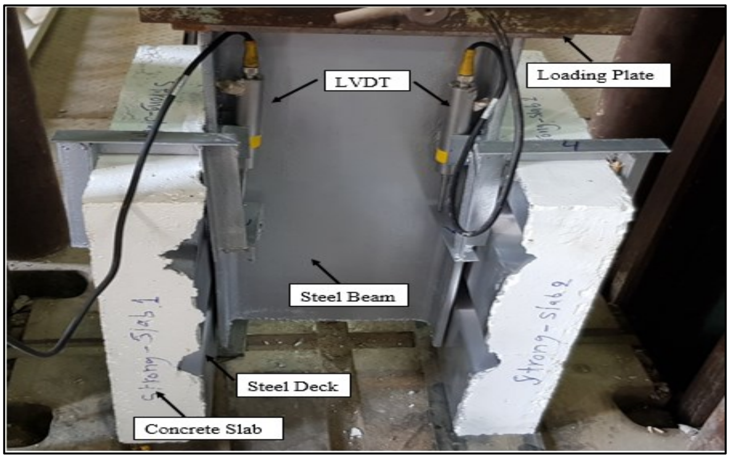



**Figure 7: Push-out test setup.**

It was made from ordinary Portland cement, fine aggregate (sand) of zone II, and coarse aggregate of 12.5 mm maximum size. The cement was conforming to the Iraqi Specification No.5/1984 [14], and the aggregates grading complying with the of the Iraqi Specification No.45/1984 [15]. The cement-sand-aggregate ratio was 1:1.2:1.8 by weight, the water-cement ratio was 0.301 by weight, and superplasticizer (SikaViscocrete-5930) dosage was 0.8% of cement weight.
Tensile coupons for this investigation were prepared following ASTM 370 specification [16] from the top chord and bottom chord. The results of the tensile properties of steel joist components are given in Table 2.

**Table 2: Test results of deep beam specimens**

| 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 |
| Welded Wire Mesh | Ø 6 | 543 | 568.22 |
| Headed Shear Connector | Ø 16 | 425 | 581.33 |

## 4. Experimental Results

*I. Composite open web joists test results*

The following sections present comparisons and discussions of the load-deflection, type of failure mode, load-strain behavior of the three composite open web joists under static loading. The flexural stiffness of the composite joist can be indicated from load-deflection behavior, while the overall performance of the composite system can be investigated from load-strain behavior as follows:

*1. Load-deflection behavior and failure mode*

As illustrated in Figure 8 and Table 3, the load-deflection behavior was similar for the composite open web steel joists designed with full shear connection for both span-to-depth ratios 13.5 and 15.5. They showed a linear behavior to about 270 kN and 320 kN, respectively. Then, they reached the ultimate capacity with a difference less than 10 percent, comparing to the third specimen, which designed with partial shear connection, a significate increase in the flexural stiffness and ultimate capacity was noted. It can be also noted that there was an increase in deflection of the specimen (N13.5RUM) less than 50% compared with the specimen (N13.5ROM). However, the ultimate capacity of these specimens was achieved when yielding occurred in the bottom chords. Further, the failure was typically followed by the crashing of concrete resulted in the unloading of the joists.

Crashing of concrete close to shear span was observed for specimens (N13.5ROM) and (N13.5RUM), followed by excessive delamination of the steel sheet from the concrete slab. Figure 9 shows the composite open web steel joists after failure, which illustrates the similarity in their failure modes, while observation of failure for the specimen (N15.5ROM) indicates crashing within the midspan, followed by delamination of the profiled sheet from the concrete slab. First compression diagonal member buckling was observed for specimens (N13.5ROM) and (N15.5ROM) before the ultimate load. For specimen (N13.5RUM), web local buckling was indicated for nearly all compression web members close to the supports.

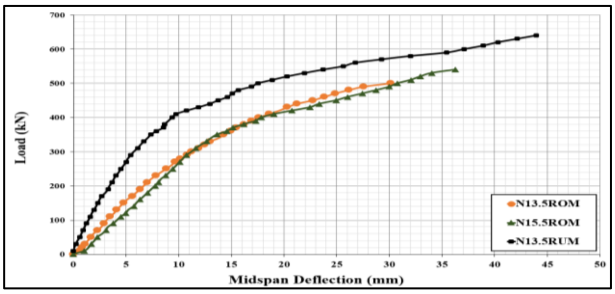



**Figure 8: Load– midspan deflection curves of the tested specimens.**

**Table 3: Ultimate strength and midspan deflection of the tested specimens**

| Specimen | Failure Load (kN) | Mid-Span Deflection at Failure Load(mm) |
|---|---|---|
| N13.5ROM | 500 | 30.12 |
| N15.5ROM | 540 | 36.27 |
| N13.5RUM | 640 | 43.96 |

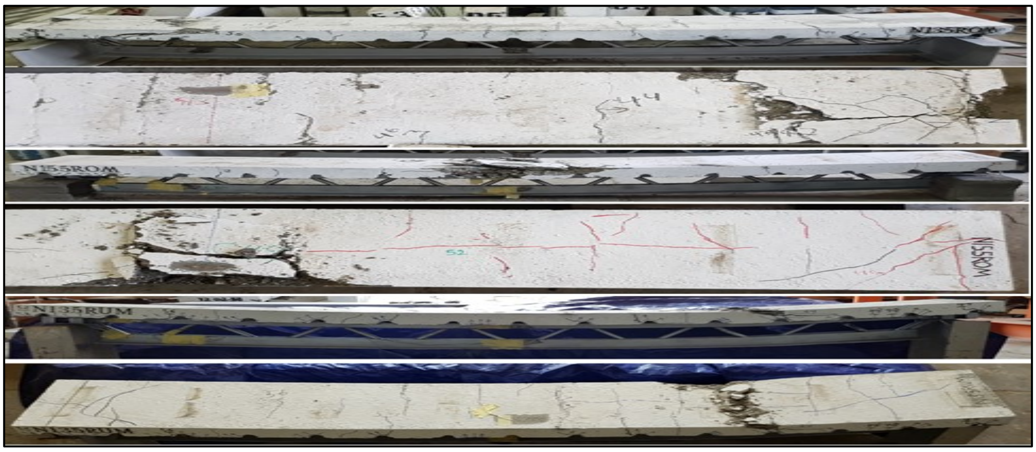


**Figure 9: Composite joist specimens at failure.**

*2. Load-strain behavior*

Several strain gauges have been mounted to obtain load-strain graphs for the three specimens. Figure 10 presents the load-strain behavior in the concrete slab and the top and bottom chords at the midspan of the composite open web joists. It can be seen from the strain behavior of the top chord of the specimen (N13.5ROM) that the neutral axis remained within the top chord up to failure, whereas for the specimen (N15.5ROM), the graph exhibited compression strain up to approximately about 350 kN. This indicates that the neutral axis was below the top chord, then it moved to be within the concrete slab, after yielding of the bottom chord. For specimen (N13.5RUM), the graph indicates that the neutral axis was within the top chord up to about 450 kN. Then, the strains in the horizontal leg of the top chord decreased and reversed to tension, which means that the neutral axis moved to the concrete slab after bottom chord yielding. The strain graphs of the bottom chords showed that the strain values for all specimens at failure are equivalent to stresses exceeds the theoretical yield stress of the steel. This indicates that the failure of all specimens is characterized by the yielding of the bottom chords as designed.

As expected, the concrete slabs strain behavior for all specimens are showing completely compression strains up to failure. The specimen (N15.5ROM) showed a maximum strain value of 2925 micro-strain at failure.

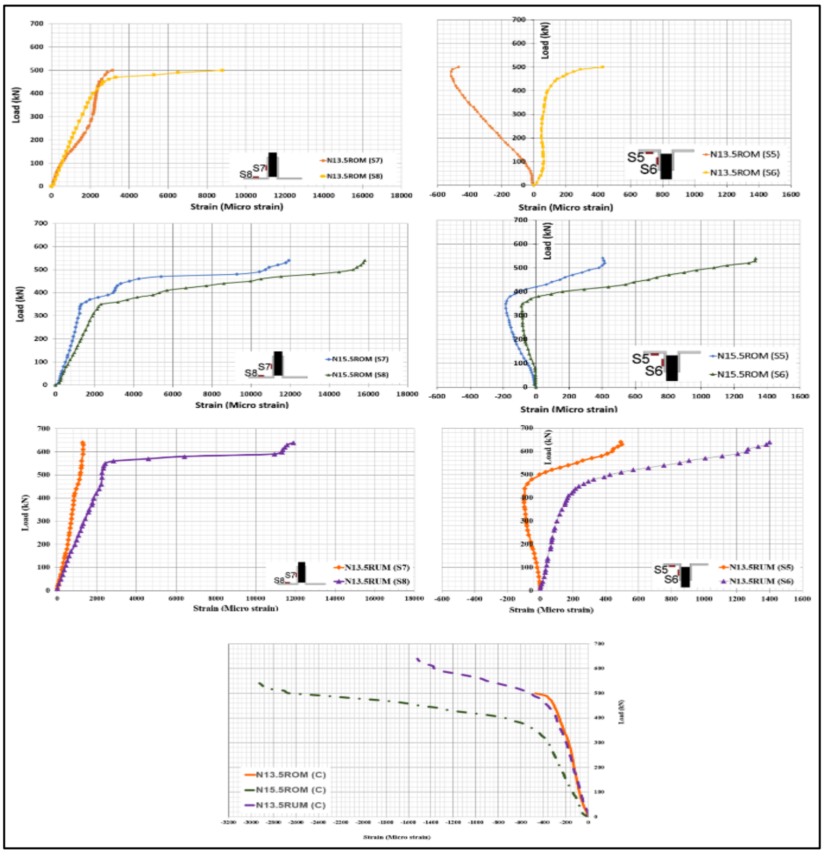



**Figure 10: Load-strain behavior of the tested specimens.**

*II. Push-out test results*

The detected failure mode in all pushout specimens resulting from concrete crushing and excessive splitting of the concrete slabs from the profiled sheet, as shown in Figure 11. Considering the load-slip behavior, as shown in Figure 12, it can be observed that a nonlinear behavior was recognized for the test specimens. The average strength of 42.5 kN per stud was obtained from the three push-out tests. The average concrete strength obtained from a compression test of the concrete cylinders was 40.63 Mpa.

As illustrated in Table 4, several comparisons of stud strength capacities were made between results from pushout test, back-calculated from composite joists tests, and predicted strengths from the AISC specification [8], Eurocode-4 [9], NZS 3404.1 [10], SJI [11], and BS 5950 [12] using measured material properties. The Qpo values represent stud strength from the push-out test, while shear stud strengths Qbc were back-calculated using the experimental moment from the composite open joist tests. As can be seen from the table, the pushout test-to- predicted ratios compare favorably for SJI predictions, but it becomes unconservative by 57% for AISC and NZ provisions, 86% for EC, and 61% for BS5950.

A further comparison was made between two values of moment strengths for composite joists are presented in Table 5. The moment strength $M_{po}$ was calculated as per Steel Joist institute SJI, [11], and Azmi [17] depending on shear stud strength $Q_{po}$, while M exp. represents the maximum moment calculated from the ultimate load of experimental composite joist tests. It can be noticed that the calculated moment depending on stud strength from the pushout test is quite low compared with the actual moment values from the static test, especially for under-connected composite joists.

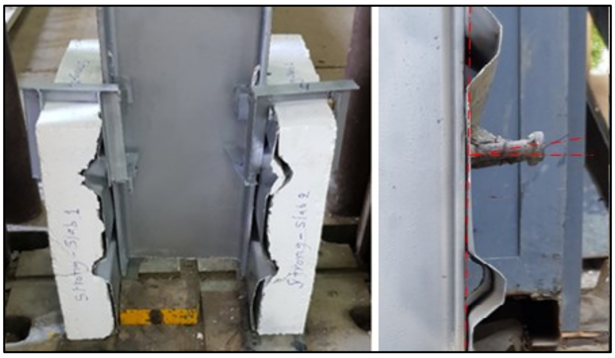


**Figure 11: Typical cracking pattern and stud deformation of push-out test specimen**

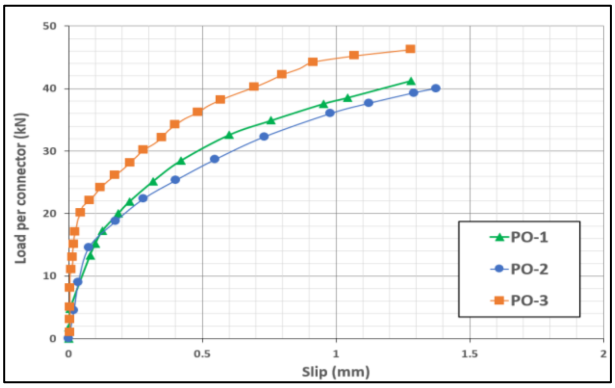



**Figure 12: Load-slip curves of push-out specimens**

## 5. Conclusions

In this paper, the push-out tests were used to determine the proper amount of shear connection, while the composite open web steel joist tests were significant to investigate the failure mode of full-size specimens. Furthermore, two analytical methods were performed to compare the predicting values of load per connector with the experimental results. According to both analytical and experimental results, the following conclusions were remarked:

1. According to the composite joists' experiments, the headed stud shear connectors withstand the integrity of the composite action until they reach the flexural strength failure without any deformation in steel top chord.
2. Both specimens designed with same span-to-depth ratio and different shear connection degree failed similarly, crushing in the composite slab close to the supports/delamination, the results from the load-deflection behavior showed that the composite open web joist designed with partial shear connection had a relatively higher ultimate capacity accompanied with a significant increase in deformation.
3. For the composite open web joist designed with various span-to-depth ratios, although they had similar load-deflection behavior, the specimen with higher depth had a lower ultimate capacity and deflection.
4. Based on load-stain curves, the tensile strain in the bottom chords for all specimens increased dramatically in a nonlinear behavior, this indicates that the failure was controlled by bottom chords yielding before crushing in the composite slab and delamination.
5. The load-slip response of the push-out test specimens showed a ductile behavior, and the controlling failure of the specimens was the separation between the slab and the steel deck and crashing of the concrete slab.
6. Several stud strength predictions have been developed using five reference codes (AISC, Eurocode-4, NZS 3404.1, SJI, and BS 5950-3.1) with the experimental results. This comparison clearly shows that there were significant differences between the stud strength values. Although, the results of the comparison showed that the stud strengths from SJI and EC correspond well to the values based on push-out. But, the stud strengths from the pushout test were extremely lower than anticipated by the other codes.

7. SJI institute provides conservative results in calculating the flexure moment capacity of the composite open web steel joists, especially for under-connected shear connection.

**Table 4: Stud strength from pushout test, back-calculated from composite joist experiments and predicted by the standards**

| Specimen | $Q_{po.}$, (kN) | $Q_{AIS}$, (kN) | $Q_{EC-4}$, (kN) | $Q_{NZ}$, (kN) | $Q_{SJI}$, (kN) | $Q_{BS}$, (kN) | $Q_{bc.}$, (kN) | $Q_{po}$/ $Q_{AISC}$ | $Q_{po}$/ $Q_{EC}$ | $Q_{po}$/ $Q_{NZ}$ | $Q_{po}$/ $Q_{SJI}$ | $Q_{po}$/ $Q_{BS}$ | $Q_{po}$/ $Q_{bc}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| N13.5ROM | 42.5 | 74.47 | 49.54 | 75.19 | 46.31 | 70.77 | 51.61 | 0.57 | 0.85 | 0.56 | 0.91 | 0.60 | 0.82 |
| N15.5ROM | 42.5 | 74.63 | 48.56 | 73.71 | 46.31 | 69.38 | 73.38 | 0.57 | 0.87 | 0.57 | 0.91 | 0.61 | 0.58 |
| N13.5RUM | 42.5 | 74.47 | 48.97 | 74.32 | 46.31 | 69.95 | 173.80 | 0.57 | 0.86 | 0.57 | 0.91 | 0.60 | 0.24 |

$Q_{po}$= stud strength from push-out test results.
$Q_{AISC}$=calculated stud strength using AISC provisions [8].
$Q_{EC-4}$=calculated stud strength using Eurocode provisions [9].
$Q_{NZ}$ =calculated stud strength using New Zealand provisions [10].
$Q_{SJI}$=calculated stud strength using SJI provisions [11].
$Q_{BS}$=calculated stud strength using British Standard provisions [12].
$Q_{bc}$ =back-calculated stud strength the experimental test of composite joist.

**Table 5: Moment capacities of the composite open web steel joists.**

| Specimen | $M_{po}$, (kN. m) | $M_{exp.}$, (kN. m) |
|---|---|---|
| N13.5ROM | 142.8 | 153.9 |
| N15.5ROM | 128.5 | 166.2 |
| N13.5RUM | 116.6 | 197.0 |

$M_{po}$= calculated moment strength of composite joist using concrete strength, and $Q_{po}$.
$M_{exp.}$ = moment strength from the experimental test of composite joist.

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