Experimental study of steel-concrete composite beams with slab opening

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Summary
This study investigates experimentally the effect of openings in the concrete slab of the composite beams. Composite beams consisted of concrete slab connected with steel I-beams by steel headed stud connectors is used in the study with eleven specimens. The test specimens are designed to test and failed in flexure. The test specimens are classified depending on the variable parameters into the following groups: control sample; opening ratio; ratio the short to the long dimension of opening; thickness of the concrete slab; grade of compressive strength; strengthen of opening by steel plate. The results of the study indicate that the general trend in the ultimate load is to increase with increasing thickness of the concrete slab and increasing the compressive strength of concrete. While the ultimate load decreased when increasing the opening ratio because decreasing the effective width of the concrete slab and the cracks develop when the opening was near to the applied loads. Also, the distribution of shear connectors in place of opening on both sides and present the diagonal reinforcing rebars about the opening minimize from the significant decrease for the ultimate load.

Keywords: Steel-concrete composite beam; slab opening; Opening in concrete flange

1. Introduction
Steel-concrete composite floor systems are widely used in industrial and residential buildings. Compared with conventional reinforced concrete floors, steel composite floors have major advantages in their bending resistance and stiffness by fully utilizing the material strength of both steel and concrete, and taking advantage of reducing self-weight and/or beam height and...
speeding up construction. To satisfy functional requirements such as placing heating, ventilating, water pipes, and electric wires, the floors have to be cast with openings in many cases.

When there are openings in the floor, the concrete flange of steel-concrete composite beam is weakened and a stress concentration occurs at the openings, which may significantly affect the flexural strength and rigidity of structures. If the composite effects between the concrete slab and steel beam are not considered in the design, i.e., ignoring the composite action, the construction cost will be increased due to this conservatism. Therefore, it is necessary to consider the composite action and effects of openings on the flexural strength of steel-concrete composite beams.

A lot of studies have composite beams with web openings and described the procedures for calculating the shear capacity and deflections of beams. Also, investigations of the web opening effects on composite beam performance were carried out by many other researchers from different aspects [1-4]. Nie JG [5] had carried out the test on steel-concrete composite with an opening rate below 50 % in the concrete slab as shown in Fig. 1(a), to find failure modes, load versus deformation relations, stress distribution in the concrete slab. The opening rate was defined as the ratio of the area of the cross-section with openings and the section without openings in the concrete flange. Besides that and based on the elastic finite element model and series theoretical derivation, the equation for calculating the elastic rigidity of steel-concrete composite beams with full openings in the concrete slab as shown in Fig. 2(b) by Nie JG [6].
In this paper, and as the successive research on the mechanical behavior of steel-concrete composite beams with slab openings, the research studies other sides in addition to the opening rate. From these sides, the crack patterns, ratio of the short to the long dimension of the opening, grade of concrete, thickness of the concrete slab, strengthen of opening by steel angles and plates, and effects the opening on the relative slip between the concrete slab and steel beam.

2. Experimental study

2.1. Specimens

A specimen without opening was tested as a control specimen and another ten specimens were tested in five groups with two specimens in each group. The opening was in the concrete flange at mid-span of each specimen directly. The concrete slab (500 mm in width) is compositely connected to an I-section (IPE140) steel beam with a span length of 2250 mm. The dimensions of the (IPE140) are: total depth = 140 mm; flange = 73 mm by 6.9 mm; and web = 112.2 mm by 4.7 mm. Shear studs of 12 mm in diameter and 50 mm in length with head diameter 20.2 and his height 8 mm were welded to the top flange of the steel beam starting from the support with fifteen studs in each side of the specimen by spacing 60 mm along the centerline of the steel beam. Steel plates (8 mm) and angle steel (70×70×5) mm were used in the last group. The measured mean compressive strength of the concrete using cubic model is f_{cu}=30 MPa and f_{cu}=60 MPa, and the steel used for the I-section beam has a mean tensile yield strength f_y=312 MPa, angle steel f_y=224.5 MPa, steel plates f_y=308.7 MPa, and reinforcing rebars (8 mm) f_y=454.6 MPa.
The five groups of specimens have an opening ratio of 35% and 55% in each group were the opening ratio is defined as the percentage of opening width to concrete slab width. The opening ratios and other parameters of all tested specimens listed in Table 1 and detailed in Fig.2.

Table 1 Parameters of specimens

| Specimen | Concrete slab thickness (mm) | Opening ratio (%) | Size of opening (mm×mm) | Short to long opening size | f_{cu} (MPa) |
|----------|-----------------------------|-------------------|-------------------------|---------------------------|--------------|
| CB Control | 70                          | -----             | -----                   | -----                     | 30           |
| CB1      | 70                          | 35                | 175×175                 | 1:1                       | 30           |
| CB2      | 70                          | 55                | 275×275                 | 1:1                       | 30           |
| CB3      | 70                          | 35                | 175×350                 | 1:2                       | 30           |
| CB4      | 70                          | 55                | 275×412.5               | 1:1.5                     | 30           |
| CB5      | 90                          | 35                | 175×175                 | 1:1                       | 30           |
| CB6      | 90                          | 55                | 275×275                 | 1:1                       | 30           |
| CB7      | 70                          | 35                | 175×175                 | 1:1                       | 60           |
| CB8      | 70                          | 55                | 275×275                 | 1:1                       | 60           |
| CB9      | 70                          | 35                | 175×175                 | 1:1                       | 30           |
| CB10     | 70                          | 55                | 275×275                 | 1:1                       | 30           |

Fig. 2. Dimensions of specimens (unit = mm)
Reinforcing rebars in the concrete slab and passing in the openings were put next to the openings and in addition to that two layers from four reinforcing rebars (8 mm diameter) were found about the opening in the diagonal shape as shown in Fig. 2.
2.2. Instrumentation

All the specimens were simply supported, loaded in two symmetrical points about the mid-span of the beam with a spacing of 750 mm. The load was transferred through a distributing beam to the sleeper beam normal to the axis of specimen, and then to the top concrete slab. Also, dial gauges and strain gauges were used to measure the vertical deflection and normal strain.

3. Experimental results

The main experimental results are summarized in Table 2, where $P_{crf}$ = load of the first crack at the bottom face of the concrete slab; $\Delta_{crf}$ = mid-span deflection corresponding to load of the first crack at the bottom face; $P_{cro}$ = load of the first crack at the opening; $\Delta_{cro}$ = mid-span deflection corresponding to load of the first crack at the opening; $P_u$ = ultimate load of the specimen; $\Delta_u$ = mid-span deflection corresponding to the ultimate load.

It was observed that with the increase of load, the curvature of the composite section increased, and the neutral axis shifted upward. When the top of the concrete slab arrived its limiting strain, the composite beam reached the ultimate bearing capacity, or when the shear connector failed the steel beam reached to the plastic stage the load was dropping. Good ductility was observed, as shown in Table 2 by the values (from 2.19 to 4.47).

| Specimen | Opening ratio (%) | $P_{crf}$ (KN) | $\Delta_{crf}$ (mm) | $P_{cro}$ (KN) | $\Delta_{cro}$ (mm) | $P_u$ (KN) | $\Delta_u$ (mm) | $\Delta_u/\Delta_{crf}$ |
|----------|------------------|----------------|---------------------|----------------|---------------------|-----------|----------------|---------------------|
| CB control | ---- | 90 | 5.05 | ---- | ---- | 162 | 22.57 | 4.47 |
| CB1 | 35 | 80 | 5.30 | 100 | 6.52 | 156 | 23.27 | 4.39 |
| CB2 | 55 | 110 | 7.14 | 70 | 4.36 | 154 | 20.88 | 2.92 |
| CB3 | 35 | 90 | 6.41 | 90 | 6.41 | 155 | 21.18 | 3.30 |
| CB4 | 35 | 120 | 8.55 | 70 | 4.27 | 152 | 19.02 | 2.22 |
| CB5 | 35 | 70 | 3.12 | 160 | 8.35 | 182 | 13.85 | 4.44 |
| CB6 | 55 | 90 | 5.83 | 90 | 5.83 | 158 | 16.93 | 2.90 |
| CB7 | 35 | 80 | 3.67 | 140 | 7.03 | 200 | 16.86 | 4.59 |
| CB8 | 55 | 140 | 8.59 | 100 | 5.28 | 190 | 18.85 | 2.19 |
| CB9 | 35 | 80 | 4.72 | 150 | 13.05 | 155 | 16.08 | 3.41 |
| CB10 | 55 | 100 | 5.67 | 120 | 7.19 | 145 | 15.46 | 2.73 |
As stated in Experimental work, the specimen CB Control is the control specimen without opening. The first crack load was about (55.56 %) from the ultimate load. When increasing the applied load, the cracks were appearance with direct to upward of the concrete surface. Until in upper loading almost the ultimate load, the crack starting in lateral direction formed longitudinal crack along the line of shear connectors to the end specimen because of the dowel action of shear connectors. The ultimate load was (162 KN) and at this moment of loading, the load was dropped down.

In the first group, the first crack was formed in the bottom face of the concrete slab then in the opening for specimen CB1. While the first crack was in the opening firstly and at the bottom face in specimen CB2. The ultimate load was decreased by (3.70 %) and (4.94 %) from the ultimate load of the control specimen (without opening) for specimens CB1 and CB2 respectively. The increase in the first crack load at the bottom face of the slab and the decrease in the ultimate load between these specimens because of the increase in the opening ratio led to a decrease in the effective width and difference in the location of the neutral axis.

Content the second group on the parameter ratio of short to the long dimension of the opening. The ratios were (1:1.5) and (1:2). These ratios were used to enlarge the size of the opening in which the opening width was the same. The first crack was in the opening and bottom face of the concrete slab together in specimen CB3, while was in the opening thereafter in the bottom face in the specimen CB4. That retains to near the edge of the opening to the line load because of the large opening ratio and large ratio for the short to long dimension opening. The decrease in the ultimate load was due to the increase in the opening ratio and this difference led to a difference in the failure mode from the dowel action then steel beam for opening ratio (35 %) to the crushing failure in the top face of concrete slab for opening ratio (55 %).

The variable parameter in the third group was the increase in the thickness of concrete slab from (70 mm) in the first group to (90 mm) in the current group. The first crack was in the bottom face and the upper increments of load, the crack appeared in the opening. This was in the specimen CB5 opposite the specimen CB1. While the first crack in the specimen CB6 was in the opening and the bottom face at the same moment, and this retains the changing thickness of the concrete slab. The decrease in the ultimate load because of the decrease in the effective width of
the concrete slab (increasing the opening ratio). Also, the mode failure was various by this reason from the dowel action in specimen CB5 to the crushing failure in the top concrete slab in specimen CB6.

Fourth group content the parameter of compressive strength of concrete. The increase in the compressive strength about (50%) from \( f_{cu} = 30 \text{ MPa} \) to \( f_{cu} = 60 \text{ MPa} \). The first crack was firstly in the bottom face of the slab in specimen CB7 while in the opening for specimen CB8. This discrepancy in the first crack load because of the increase in the opening ratio, wherever in the large opening leads to a concentration of the stresses because near the sides to the applied loads. The ultimate loads were higher than the ultimate loads in the first group but the reduction in the same group retains the opening ratio and this led to differences in the failure mode from dowel action in specimen CB7 to crushing failure at the upper concrete slab in specimen CB8.

The fifth group contains the parameter of strengthening the opening in the first group by steel plate and angle sections. They were connected both and with the steel beam by welding connection. The first crack load in the opening was larger than the first crack load at the same opening in the first group. This strengthening decreased the mid-span deflection but it wasn't improving the ultimate load. The failure mode here was a failure of the dowel action then happened the plastic hinge in the steel beam.

The mid-span deflection versus the applied load of each group is shown in Fig. 3. It can be seen that when the load is less than about (50%) of the ultimate load, the specimens performed in a linear-elastic manner. With a further increase in loading, the specimens performed nonlinearly due to the yielding of steel beams and cracking/crushing of concrete slabs. Fig. 4 show some photos from tested specimens and the crack patterns.

Relative horizontal displacement occurs at any flexural composite member due to bending. Usually, this horizontal displacement is not equal in the concrete and steel component of the composite section, so there is a differential displacement between them and this called slip displacement. In the present study, end slips at the ends of the steel beams were recorded for each load increment. End slip readings are denoted as \( S_1 \) and \( S_2 \) at both ends of the specimen and the maximum slip listed in Table 3 in addition to the ultimate load for each specimen.
Fig. 3 Mid-span load versus deflection
Fig. 4 Crack patterns at failure for some specimen
Table 3 Maximum end slip

| Specimen | Ultimate Load | End Slip | Percentage Variation % |
|----------|---------------|----------|------------------------|
|          | $P_u$ (KN)    | $(S1)_{max}$ (mm) | $(S2)_{max}$ (mm) | Ave. (mm) |
| CB Control | 162        | 3.67 | 3.42 | 3.55 | -----
| CB1      | 156        | -3.70 | 3.37 | 3.84 | 3.61 | +1.69 |
| CB2      | 154        | -4.94 | 1.27 | 1.65 | 1.46 | -58.87 |
| CB3      | 155        | -4.32 | 3.21 | 3.78 | 3.24 | -8.73 |
| CB4      | 152        | -6.17 | 1.87 | 1.56 | 1.99 | -43.94 |
| CB5      | 182        | +12.35 | 2.58 | 3.23 | 2.91 | -18.03 |
| CB6      | 158        | -2.47 | 1.17 | 1.44 | 1.38 | -61.13 |
| CB7      | 200        | +23.46 | 1.74 | 2.28 | 2.01 | -43.38 |
| CB8      | 190        | +17.28 | 0.87 | 1.06 | 0.97 | -72.68 |
| CB9      | 155        | -4.32 | 3.78 | 3.54 | 3.66 | +3.10 |
| CB10     | 145        | -10.49 | 3.86 | 4.32 | 4.09 | +15.21 |

The comparison of the end slip results for the tested specimens shows that the end slip results of specimens (CB2, CB4, CB6, and CB8) are less than that for specimens (CB1, CB3, CB5, and CB7). This because of the decrease in the effective width of the concrete slab by (20 %) from opening ratio (35 %) to (55 %) and transition of stresses for specimens in the top fiber of concrete fast than stresses in concrete about shear connectors.

Increasing the thickness in concrete slab for specimens (CB5 and CB6) leads to a decrease, in the end, slips compared with the control specimen and specimens (CB1 and CB2). The decreasing percentages compared with the control specimen were (18 and 61) % respectively. Also, in case increasing the compressive strength of concrete leads to a reduction, in the end, slip as shown in specimens (CB7 and CB8) by (43.4 and 72.7) % respectively corresponding to the control specimen.

When the opening is strengthening by steel plates, the end slip was increasing in samples (CB9 and CB10) by percentage (3.1 and 15.21) % respectively. This is due to the transmission of stresses from the top fiber of concrete to the shear connectors and the concrete surrounding it.
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