Assessment of the flexural capacity of composite reinforced concrete beams using experimental tests and finite element analysis

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Abstract One of the main governing matters points in studying the composite reinforced concrete beams (CRC) is the force transmission mechanism at the interface between the concrete and the steel section. In this research, a new connection method for CRC beams consisting of reinforced concrete and steel T-section is studied. In this method, the stirrups are utilized to perform as shear connectors. The experimental part of the study includes studying the flexural behavior of the CRC beam with different degrees of interaction. The theoretical part of the study includes constructing a three-dimensional finite element model using ABAQUS software and validating the model using the experimental results. The model was verified by comparing the critical local and global responses of the CRC beams such as the beam deformation, load at which the steel T-section reached yield point, and concrete cracking and crushing. The model showed a good correlation for the estimation of ultimate load with an accuracy of 105% was achieved.

Keywords: Composite, CRC beams, stirrup connectors, ABAQUS.

1 Introduction
The performance of composite reinforced concrete beam (CRC beam) for static and dynamic loads depends mainly on the mechanism at which the force is transmitted at the interface of the steel beam and the concrete[1]. The stud connection used in composite beams uses welded studs to connect the steel beam to the concrete[2]. However, the process of welding the stud to the steel section is rather expensive and require special tools to be completed on-site. The composite dowel was proposed as a method for utilizing the slab reinforcement to act as shear connectors by cutting the web of the steel section in several shapes so that the reinforcement pass through them and provide the connection[3]. Nonlinear behavior of the composite beams has been studied by conducting experimental test [4–7] or by using the finite element modelling programs to build a two or three-dimensional model that simulates the behavior of the beam.

In this research, the method used to provide the shear connectors is by utilizing the stirrups of the beam. The connection is achieved by drilling the steel T-section at the stirrup location, and the stirrups are allowed to pass through the drilled holes in the web. The research includes testing four large scale CRC beams and one R.C beam. The results are used to study the degree of interaction effect on the flexural capacity and to validate the three-dimensional model.

In the theoretical part, the concrete in compression is idealized as elastic-plastic material and in tension as linear elastic material up to cracking. The damage plasticity model was used as well. The
same model used also to accommodate stiffness degradation due to cracking. The Finite Element Model FEM is validated by comparing the critical local and global responses of the CRC beam such as the beam deformation, load at which the steel T-section reached yield point, and concrete cracking and crushing. The benefit of the proposed CRC beam in the current study, is that it can be easily constricted with minimum specialized tools and can be easily modified on site which makes it more economical.

2 Experimental work

As a part of this study, experimental tests were conducted on four large scale CRC beams and one R.C beam to investigate the flexural response of the beam. Each beam has a length of 3000mm with a clear span of 2710mm, a width of 175mm, and a depth of 350mm. The cross-section of the beam consists of reinforced concrete beam and steel T-section as shown in Figure (1). The descriptions of the tested specimens are listed in Table 1. The testing configuration for the flexural specimens is shown in Figure (2). Table 2 illustrates the properties of the material used in the experimental part of the study. The specimens include one conventional reinforced concrete beam S1, two CRC beams with 100% degree of interaction S2 and S3 for sagging and hogging test respectively, and two CRC beams with 48.8% degree of interaction S4 and S5 for sagging and hogging test respectively.

Table 1. Description of the specimens

| Specimen Designation | Degree of interaction (no. of stirrups) | Dimensions (mm) |
|----------------------|----------------------------------------|-----------------|
|                      |                                        | Height | Width |
| S1                   | R.C                                    | 350    | 175   |
| S2                   | 100 (43)                               | 350    | 175   |
| S3                   | 100 (43)                               | 350    | 175   |
| S4                   | 48.8 (21)                              | 350    | 175   |
| S5                   | 48.8 (21)                              | 350    | 175   |

Figure 1. Cross-section details (a) composite reinforced concrete beams, and (b) reinforced concrete beam
Figure 2. Testing configuration for the bending test

| Details                     | Description                          | Value |
|-----------------------------|--------------------------------------|-------|
| Concrete                    | Elastic modulus, MPa                 | 25570 |
|                            | Poisson’s ratio                      | 0.2   |
|                            | Compression strength (cylinder), MPa | 29.6  |
| 16mm reinforcement bars     | Elastic modulus, MPa                 | 201282|
|                            | Poisson’s ratio                      | 0.3   |
|                            | Ultimate tensile strength, MPa       | 636   |
|                            | Yield tensile strength, MPa          | 527   |
| 8mm reinforcement bars      | Elastic modulus, MPa                 | 202150|
|                            | Poisson’s ratio                      | 0.3   |
|                            | Ultimate tensile strength, MPa       | 490   |
|                            | Yield tensile strength, MPa          | 314   |
| Steel T-section             | Elastic modulus, MPa                 | 204263|
|                            | Poisson’s ratio                      | 0.3   |
|                            | Ultimate tensile strength, MPa       | 508   |
|                            | Yield tensile strength, MPa          | 376   |

2.1 Failure modes

The reinforced concrete beam S1 is a simply supported beam under four-point loading. After loading the first crack of the beam appeared at a load equal to 27kN, then the beam suffered from yielding of the 16mm bars in tension at a load of 173.4kN followed by concrete crushing failure at the top compression zone at mid-span at a load equal to 178kN. Figure 3) shows specimen S1 failure. The CRC beam with 100% degree of interaction between the concrete and steel T-section S2, exhibited more cracks at the tension zone of the concrete which start from a load of 81kN until a load of 260kN. After this load, the concrete at compression zone crushed at top of the mid-span region, as shown in Figure 4). The failure started when the 8mm bars in tension reached its yield point at 228kN, then the steel T-section reached its yield point at a load equal to 262kN. The strain in concrete increased until concrete crushed at a maximum load of 340kN.

Specimen S4 represents the CRC beam with 48.8% degree of interaction between the concrete and steel T-section. The beam failure mode was similar to that of specimen S2, started with a flexural crack at a load equal to 45kN and failed by the crushing of concrete, as shown in Figure 5). The 8mm bars in tension reached its yield point at a load equal to 206.1kN followed by yielding of the steel T-section at a load equal to 207kN. The concrete reached the crushing point at a load of 315kN.
Specimen S3 is CRC beam with 100% degree of interaction between concrete and steel T-section. This beam was tested to evaluate the hogging bending capacity of the CRC beam. Flexural cracks at bottom of mid-span developed at a load of 53kN. These cracks started widening excessively and the
beam failed by tension failure (yielding) of the reinforcement as shown in Figure 6). The failure of the beam started when the steel T-section reached its yield point in compression at a load equal to 180kN. The 16mm reinforcement reached its yield strain in tension at a load equal to 212.8kN. Finally, strain in the tension reinforcement starts increasing rapidly until the failure point with a maximum load value of 250kN.

Figure 7 shows specimen S5 which is a CRC beam with 48.8% degree of interaction tested to evaluate the hogging flexural strength of the beam. The beam developed flexural cracks that start appearing at a load equal to 35kN and continued until the beam reached its ultimate load-carrying capacity of 250kN after which the beam undergoes excessive deflection without an increase in load value indicating yielding of tension reinforcement.

The behavior of the beam was similar to that of CRC beam S3 started by yielding of steel T-section in compression at a load equal to 158.86kN, followed by yield in the 16mm bar in tension at a load of 162.61kN. The concrete reached crushing failure at a load of 250kN. Table 3 summarizes the failure modes for the tested specimens, cracking load, and maximum loads. It was found that the degree of interaction increased the flexural strength when the steel section was in tension and made no effect on the maximum load value when the section was in compression.

From the strain value of the beams, it can be seen that increasing the degree of interaction increased the load at which the steel T-section yield for CRC beam with 100% degree of interaction by 1.27 times that of the CRC beam with 48.8% degree of interaction when the steel T-section was in tension, and by 1.13 times when the steel T-section was in compression.
Table 3. Test result for specimen subjected to bending

| Beam | Bending region | Degree of interaction (no. of stirrups) | First cracking Load (kN.) | Maximum load (kN.) | Failure mode |
|------|----------------|------------------------------------------|---------------------------|-------------------|--------------|
| S1   | Sagging        | Reinforced concrete                      | 27                        | 178               | Yielding of tension reinforcement followed by crushing of concrete at compression zone |
| S2   | Sagging        | 100 (43)                                 | 81                        | 340               | Crushing of concrete at compression zone |
| S4   | Sagging        | 48.8 (21)                                | 45                        | 315               | Crushing of concrete at compression zone |
| S3   | Hogging        | 100 (43)                                 | 53                        | 250               | Yielding of tension reinforcement |
| S5   | Hogging        | 48.8 (21)                                | 35                        | 250               | Yielding of tension reinforcement |

2.2 Load-deflection behavior

Based on the load-deflection relationship of beams up to and beyond maximum load the behavior can be distinguished as brittle or ductile behavior, and the stiffness can be found as the slope of the load-deflection curve [8].

The behavior can be divided into three distinctive parts, the behavior at the uncracked stage of loading, the cracked section behavior up to the service load of the beam, and the final failure stage of the beam. The tangential stiffness and secant stiffness of the beams calculated from the slope of the mid-span load-deflection curves is shown in Table 4. It can be concluded from the results that the value of stiffness was affected by the degree of interaction when the steel section was located in tension, the value was higher for the beam with 100% degree of interaction at uncracked section stage of loading.

The same argument can be made for the beams with the steel T-section at compression zone. That effect was clear on the service load deflection at mid-span for beam S2 which was slightly less than that of beam S4. The same finding can be seen for the CRC beam with the steel T-section in compression, but in this case, the beam with 100% degree of interaction shows pronounced reduction in service load deflection. The degree of interaction seems to have a relatively small effect on the value of service load deflection at mid-span, however, the effect on the strength is clear for the beams S2 and S4 where the steel T-section was in tension. Also, the value of the maximum load deflection for the CRC beams was less than that of the RC beam S1.
Table 4. Experimental results of tested composite beams

| Beam designation (degree of interaction) | Service load (kN) | Mid-span stiffness $10^6 N.m^2$ | Mid-span deflection at maximum load (mm) | Mid-span deflection at service load* (mm) |
|---------------------------------------|-------------------|---------------------------------|-----------------------------------------|-----------------------------------------|
|                                       |                   | Tangent stiffness $K_T$ | Secant stiffness $K_S$ |                              |                                      |
| S1 (RC)                               | 118.7             | 11.66                          | 11.14                                   | 20.13                                   | 10.18                                 |
| S2 (100)                              | 226.7             | 37.60                          | 25.78                                   | 17.03                                   | 8.82                                  |
| S4 (48.8)                             | 210.0             | 28.65                          | 20.63                                   | 15.14                                   | 8.85                                  |
| S3 (100)                              | 166.7             | 20.80                          | 18.69                                   | 14.61                                   | 8.88                                  |
| S5 (48.8)                             | 166.7             | 18.73                          | 17.52                                   | 17.21                                   | 9.51                                  |

*SService load = 2/3 Ultimate load[9]

3 Finite element model

The CRC beams with 2710mm simply supported span were modelled using the ABAQUS program [10]. The load was applied using steel plates with the same dimensions used in the experimental test. Because of the symmetry of the loading, boundary conditions, and geometry only quarter model is analyzed as shown in Figure 8.

20-node brick element C3D20R are used from ABAQUS element library to model the concrete, steel T-section, 16mm bars, 8mm bars, and 8mm stirrups. By using the C3D8R element the hourglass problems[11] which commonly arise with continuum linear solid elements can be avoided. The 16mm, 8mm stirrups and 8mm bars were modelled as embedded rebar element in concrete. For the steel T-section connection with concrete the Springs/Dashpots model were used. The results of the FEM are highly affected by the mesh size. Therefore, a mesh convergence study has been conducted by running the model with different mesh size. The mesh size was changed until no further impact on the results is obtained.

![Figure 8. Mesh size for beams](image)

Various components, namely, concrete part, steel T-section, 16mm bars, 8mm bars, 8mm stirrups, and loading plates were discretized using the part by part mesh instead of meshing the global or sweep features which results in a regular structural hexahedral mesh. The mesh selected for the model is shown in Figure 8).

3.1 Concrete compressive behavior

Elastic-plastic behavior of concrete in compression including softening has been modelled according to Carreira and Chu[12]. The failure ratio option has been used to define the failure surface of the concrete.
In the present study, a ratio of the ultimate biaxial compressive stress to the ultimate uniaxial compressive stress was taken as 1.16. The ratio of the uniaxial tensile stress to the uniaxial compressive stress at failure is maintained as 0.1[13].

3.2 Concrete tensile behavior
The stress-strain relation for concrete under tension was assumed linear up to the point of concrete cracking. After cracking the tensile stress decreases linearly as the concrete softens.

3.3 Damage model
The damage model for concrete in compression was used in which the stiffness degradation variable reduces the elastic modulus for damaged concrete. Also, the tension damage was used for concrete in tension for the same reason.

3.4 Steel
The behavior of the steel is modelled using elastic-plastic models. The yield and ultimate stresses for the 16mm bars, 8mm bars, 8mm stirrups, and steel T-section are as mentioned in Table 2. The stress-strain values were taken from the stress-strain test conducted on the steel used in the experimental part.

3.5 Interaction between beam components
In the finite element analysis, the connection model between the steel T-section and concrete can be represented in several models. However, in the current study, since it is required to study the connection effect on the behavior of the beam, therefore, the shear transfer between the steel T-section and concrete is assumed to be done by three-dimensional spring elements with specified stiffness value. A model was constructed using the stiffness value for the spring as mentioned in Ref [14–18]. The stiffness value for the spring was taken as (428kN/mm).

4 Validation of Finite Element Model
The FEM was verified by comparing the theoretical results with the experimental ones. The deflection, load, stresses and strains are used in this comparison.

Table 5 shows the theoretical and experimental maximum load of the beams. The ratio of the theoretical to experimental maximum load has a maximum value of 1.17 and a minimum of 0.99 with an average of 1.05 which indicate that the F.E model gives an excellent estimation of the maximum load of the beam. Table 6 shows the deflection value at service load and maximum load for the experimental test and the F.E model. The load-deflection behavior for the experimental test and theoretical model are shown in Figures (9) to (13).

| Beam | Experimental $P_{max}$ (kN) | F.E. model ABAQUUS $P_{max}$ (kN) |
|------|-----------------------------|---------------------------------|
| S1   | 178                         | 183.52                          |
| S2   | 340                         | 397.31                          |
| S4   | 315                         | 338.00                          |
| S3   | 250                         | 248.59                          |
| S5   | 250                         | 256.55                          |
Table 6. FEM and experimental deflection values at maximum and service load

| Beam designation | Experimental midspan deflection | FEM midspan deflection | \( \Delta r_h / \Delta ex \) |
|------------------|--------------------------------|------------------------|-----------------------------|
|                  | at service load* (mm)         | at maximum load (mm)   | at service load* (mm)       | at maximum load (mm) |
| S1               | 10.18                          | 20.13                  | 10.02                       | 16.91              |
|                  |                                |                        |                             | 98.4               | 84.0               |
| S2               | 8.82                           | 17.03                  | 8.20                        | 15.13              |
|                  |                                |                        |                             | 93.0               | 88.8               |
| S4               | 8.85                           | 15.14                  | 8.32                        | 14.21              |
|                  |                                |                        |                             | 94.0               | 93.9               |
| S3               | 8.88                           | 14.61                  | 7.75                        | 15.75              |
|                  |                                |                        |                             | 87.3               | 107.8              |
| S5               | 9.51                           | 17.21                  | 8.08                        | 16.37              |
|                  |                                |                        |                             | 85.0               | 95.1               |

*Service load = 2/3 Ultimate load

Figure (9). Specimen S1 load-deflection behavior

Figure 10. Specimen S2 load-deflection behavior
**Figure 11.** Specimen S3 load-deflection behavior

| Load (kN) | Mid-span deflection (mm) |
|-----------|--------------------------|
| Service load 226.7kN | Mid span deflection |
| Point a | Steel T-section yield |
| Point d | 8mm bars yield |

**Figure 12.** Specimen S4 load-deflection behavior

| Load (kN) | Mid-span deflection (mm) |
|-----------|--------------------------|
| Service load 210.0kN | Mid span deflection |
| Point a | Steel T-section yield |
| Point d | 8mm bars yield |

**Figure 13.** Specimen S5 load-deflection behavior

| Load (kN) | Mid-span deflection (mm) |
|-----------|--------------------------|
| Service load 166.7kN | Mid span deflection |
| Point c | Steel T-section yield |
| Point d | 8mm bars yield |
4.1 Stresses and strains
Using the finite element model the stresses in the beams can be found at any location as shown in Figure 14. Furthermore, the values of strain can be compared with the experimental data recorded by the strain gauges mounted on the beam at mid-span and one forth the span.

The model was found to be accurate regarding the estimation of the yield point for the various steel components and as shown in Figures (9) to (13).

![Figure 14. Von-Mises stress distribution](image)

5 Comparison between the ACI 318-14 code, F.E, and experimental load capacity
The values of the maximum load from the experimental test and F.E model are shown in Table (5). The value of maximum load can be calculated using ACI 318-14 code[19] equation by considering the steel T-section as regular reinforcement. The steel area $A_s$ is represent one steel T-section with area $1165\,mm^2$ with yield stress of 376MPa and two 8mm bars with yield stress of 314MPa thus the area is calculated as follows:

$$A_s = 1165 + 50.2 \times 2 \times \frac{314}{376} = 1248\,mm^2$$

The effective depth of section $d$ is (320.4mm) and the steel ratio $\rho$ is

$$\rho = \frac{A_s}{bd} = \frac{1332.7}{175 \times 320.4} = 0.0238 \quad (1)$$

The steel ratio must be compared to the maximum value allowed by the code for singly reinforced beam which can be calculated using ACI 318-14 code 9.3.3.1[19] as follows:

$$\rho_{\text{max}} = 0.85 \times \beta_1 \times \frac{f'_c}{f_y} \times \frac{0.003}{0.003 + 0.004} \quad (2)$$

$$= 0.85 \times 0.84 \times \frac{29.6}{376} \times \frac{0.003}{0.003 + 0.004} = 0.024$$

where

$\rho_{\text{max}}$: maximum steel ratio (0.024)

$\beta_1$ is the concrete property value which can be calculated using equation 3.

$$\beta_1 = 0.85 - 0.05 \times \frac{f'_c - 28}{7} \quad (3)$$
\[ f'c = 0.85 - 0.05 \times \frac{29.6 - 28}{7} = 0.84 \]

\( f'c \): concrete compressive strength (29.6MPa)

\( f_y \): yield strength of the steel T-section (376MPa)

Thus, the value of the steel ratio is less than the maximum value permitted by the code. The moment capacity can be calculated using the equilibrium equation[20].

\[
M_n = \rho \times b \times d^2 \times f_y \times \left(1 - 0.59 \times \rho \times \frac{f_y}{f'c}\right) \\
= 0.0238 \times 175 \times 320.4^2 \times 376 \times \left(1 - 0.59 \times 0.0238 \times \frac{376}{29.6}\right) = 132.1kN.m
\]

where, \( M_n \) is the moment capacity of the section.

From the section moment capacity, the load-carrying capacity can be found using the moment diagram of the beam which indicate that the maximum bending moment is \( PL/6 \) were \( P \) is the applied load and \( L \) is the clear span of the beam. Therefore, the maximum load-carrying capacity for the CRC beam with the steel T-section in tension is (292.5kN). The value of maximum load calculated using the ACI 318-14 code is 86% and 93% of the 100% and 48.8% degree of interaction beams respectively which indicate the assumption of considering the steel T-section as regular reinforcement results in underestimating the capacity of the beam especially for the case of the 100% interaction beam.

Regarding the CRC beam with steel T-section in compression, the ACI code equation estimated the load-carrying capacity of 238.4kN which is 95% of the maximum load for the tested beam. For the RC beam, the load estimated using the ACI code was 90% of the experimental test.

6 Parametric study

After verifying the F.E model it can be used to study the effects of various parameters of the CRC beam such as the degree of interaction other than the ones tested in the experimental part of the current work. The degrees of interaction tested are the 48.8% and the 100%. Other degrees of interaction are studied which include (14.3%, 18.4%, 26.5%, 34.7%, 65.3%, 73.5%, 81.6%, 85.7%). The ratios were calculated by distributing the stirrups symmetrically about the mid-span of the beam. Figure 15) shows the procedure used for distributing the stirrups. The first is by considering the long stirrup as one group located between two short stirrups and changing the stirrup number in each group from 2 to 6 stirrup which gives 65.3% and 85.7% degree of interaction respectively.

The other is by considering the short stirrups as a group between two stirrup connectors and changing the number of stirrups in each group from 2 to 6 which give 34.7% and 14.3% degree of interaction respectively. Figure 16) shows the results of the parametric study. The vertical axis in the figure represent the ratio between the model maximum load to the maximum load calculated using the equilibrium equation and ACI-code (292.5kN).
A proposed approximate design method is suggested using the FE model results. The method is based on deriving an equation to calculate a factor that can be used to estimate the maximum load of the CRC beam using the regular design methods for R.C beam. The factor is calculated by dividing the results of F.E model by the values obtained from ACI design procedure and an equation is derived using the best fit technique. From Figure (16) and for the range of cases studied, a factor $\alpha$ can be calculated which represent the ratio between the maximum load calculated using the F.E model and the maximum load calculated using the ACI-code equations. The value of $\alpha$ is calculated using equation (5) which is derived using the best-fit curve for the results shown in Figure (16).

$$\alpha = 2 \times 10^{-5} \times D^2 + 10^{-3} \times D + 1.064$$

(5)

where $D$ is the degree of interaction.
7 Conclusions

From the four CRC beams tested in this study it can be concluded that:

1- increasing the degree of interaction from 48.8% to 100% increased the ultimate loads carrying capacity of the beam by 1.08 times when the steel T-section was in tension. The maximum load carrying capacity was not affected by the degree of interaction when the steel T-section was in compression.

2- The degree of interaction effect was clear on the tangent stiffness value of the beams where increasing the degree of interaction from 48.8% to 100% increased the stiffness of the beam by 1.31 and 1.11 times for beams with steel T-section in tension and compression respectively.

3- Increasing the degree of interaction increased the load at which the steel T-section reached its yield point by 1.27 times when the steel T-section was in tension, and by 1.13 times when the steel T-section was in compression.

4- A three-dimensional finite element model is developed using the commercial software ABAQUS. The model is proved to be effective in predicting the load-deflection behavior, the maximum load value, and the failure mode of the beam.

5- The model estimates the value of maximum load for the CRC beams accurately. The maximum ratio between the F.E model and experimental results is 1.17 and the average value is 1.05.

6- For the range of tested beams, a factor was proposed to estimate the maximum load capacity of the CRC beam using the ACI equation for bending.

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