Experimental Study on Beam-Column Connections of Concrete Encased Cold-formed Steel Beams to Concrete-filled Steel Tube Columns

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Abstract. Experimental testing was done to investigate the flexural behaviours of internal roof beam-column connections. Four specimens were studied under static loads, one of which was specified as a reference reinforced concrete beam-column connection with regular bars as a conventional reinforcement for beam and column. The other specimens featured cold-formed steel plates with the equivalent area to regular bars as reinforcement, with square steel tube cross-sections filled with concrete used for columns. The results showed an increase in load carrying capacity and toughness for the experimental specimens as compared with conventional reinforcement beam-column connection. The concrete prevented local buckling of the cold-formed steel sections and improved the flexural bending capacity.

Keywords: beam-column connections, static loads, cold-formed

1. Introduction

Beam-column connections are defined as the portion of a column within the depth of the deepest beam that frames that column [1]. The complex nature of stress distribution in such connections is reflected in the descriptions of their critical behaviours. Connections with severe damage may lead to catastrophic failure due to their limited ultimate strength to resist great forces during earthquakes or blasts. Beam-column connection thus need to have adequate strength, ductility, and energy dissipation for multiple circumstances [2]. Many experimental and analytical studies have been carried out over the last 50 years on beam-column connections, and numerous parameters have been investigated in terms of their effects on the behaviours of beam-column connections, such as reinforcement percentage, transfer reinforcement, additional bars, beams being wider than columns, and concrete strength. Mohamed [3] studied the effect of the percentage of beam tension reinforcement (ρ) on the beam-column connection, noting that this has an important effect on the strength and behaviour of connections, as the deflection, maximum crack width and the spacing between cracks all decrease as ρ increases. Chen et al. [4] used a cross-section configuration of steel in a King-cross, which resembles two HS crosses, embedded in the connection to increase the shear strength and ductility. The King-cross provided higher shear strength as the shear force was not only carried by the longitudinal web but also the longitudinal flange. Lu [5] used additional diagonal bars and found that specimens with additional bars showed fewer cracks and much better control of crack capacity compared with those without them, as well as an improvement in seismic performance. Al-Amry and Ali [6] investigated hybrid reinforced concrete beam-column joint specimens under static and repeated loading with pre-axial compression.
loads, with the finding that using this hybridisation technique at different areas of connection improved both ultimate load and ductility.

Steel members are widely used in various fields of building technology due to their multiple advantages. Concrete-filled steel tube columns are also extensively used in practical engineering, as they permit quick construction with high bearing capacity, good ductility, and toughness. Cold-formed steel structures are used in a wide range of applications due to their strength to weight ratio, and simplicity of fabrication [7], [8].

In this project, an attempt was made to use cold-formed steel section (CFS) as a replacement for conventional steel reinforcement bars in beam and use square steel tubes filled with concrete as columns. The results showed increased load capacity and toughness for the specimens created in this manner as compared with conventional reinforced beam-column connection.

2. Test Programme

2.1. Description of Specimens

The experimental programme was designed to study the effect of using cold formed steel plates (CFS) to reinforce concrete beams as replacement for conventional steel bars, and the use of square steel tube filled with concrete as columns. A total of four beam-column connection specimens were constructed, all with the same materials and geometry. The length of each column was 625 mm, with 150 × 150 mm cross section dimensions, while the length of each beam was 1,350 mm, with 200 × 150 mm cross section dimensions.

2.2. Material Properties

Normal concrete with a compressive strength around 32 MPa at 28 days aging was used to cast all specimens. Ordinary Portland cement, natural sand with maximum size aggregate of 4.75 mm, and crushed gravel with a maximum size of 9.5 mm are used. Cold-formed steel sheet with thicknesses of 4 mm and 3 mm were used to reinforce the beams; these had yield strengths of 330 and 316 MPa, respectively. Square steel tube cross-sections with dimensions 150 x 150 x 3.8 mm were used for the column segments, 339 MPa yield strength. For the steel bars used, ø10 and ø12, the yield strengths were 545 and 502 MPa, respectively. Table 1 shows the properties of normal concrete

| Parameter            | Value   |
|----------------------|---------|
| w/c ratio            | 0.4     |
| Water (Kg/m³)        | 160     |
| Cement (Kg/m³)       | 400     |
| Fine aggregate (Kg/m³)| 582 |
| Coarse aggregate (Kg/m³)| 1145 |
| Super plasticizer (L/m³)| 6.5 |

2.3. Calculation of cold-formed steel plate dimensions

Cold-formed steel plates were used with the equivalent area to regular bars used for the main and shear reinforcement of concrete beams as follows:

2.3.1. Main reinforcement (tension and compression)

The equivalence between the cross-section area of a bar and the cross-section area of the required cold-formed steel plate was based on the width of steel plate (a) calculated as follows:

\[(A_b \cdot f_y)_{bar} = (A_p \cdot f_{yp})_{plate}\]

\[A_p = \text{area of steel plate} = a \times t \quad (= a \times 4\text{mm})\]
Ab = area of bar = \( \pi \frac{d_b}{4}^2 \) ( = \( \pi \frac{12^2}{4} \))
a = width of cross section CFS
t = thickness of CFS
d_b = diameter of bar (12mm)

Thus, the width (a) required to give 100% equivalence in CFS plate (4 mm thickness) with a Ø12 bar was equal to about 40 mm; this was used to create the **CF-ST1-S** specimen. As a parametric study, the percentage of equivalence area between the CFS and steel bar was reduced to 75% in the **CF-ST3-S** specimen, with a width of plate (4 mm thickness) equal to 30 mm, while the **CF-ST4-S** specimen used a width of plate equal to 40 mm, with the thickness reduced to 3mm.

### 2.3.2. Shear reinforcement

The cold-formed steel plates used for shear reinforcement had the same numbers and arrangement as the regular stirrups on the reference specimen. The spacing between the shear reinforcement was provided by creating an opening using a cutting process machine where openings near the centre of the beam did not exist; this was necessary to provide a stable area for fixation between the cold-formed plate sections and the steel tube. The first dimension of the steel plate was taken from the depth of the stirrup, while another dimension (w) was calculated from the equivalence between the cross-section area of the regular stirrup and the CFS plate as shown in the following equation:

\[(A_v \cdot f_y)_{\text{stirrup}} = (A_p \cdot f_{yp})_{\text{plate}}\]

\[A_p = \text{area of steel plate} = w \times t \quad (= w \times 4\text{mm})\]

\[A_v = \text{area of stirrup} = \frac{\pi}{4} d_b^2 \quad (= \frac{\pi}{4} 10^2)\]

w = width of CFS plate
t = thickness of steel plate
d_b = diameter of bar (10 mm)

The geometry and detailed reinforcement arrangements of the tested specimens are shown in Figures 1 to 3 and in table 2.

### Table 2. Details of tested beam-column connection specimens

| Specimen       | Beam reinforcement thickness (t) | Plate thickness | Percentage of equivalence % | Column reinforcement
|----------------|----------------------------------|-----------------|-----------------------------|------------------------|
| N-N-S (reference) | Bars                            | -               | -                           | Bars                   |
| CF-ST1-S       | CFS                             | 4mm             | 40mm                        | 100                    | Steel tube             |
| CF-ST3-S       | CFS                             | 4mm             | 30mm                        | 75                     | Steel tube             |
| CF-ST4-S       | CFS                             | 3mm             | 40mm                        | 75                     | Steel tube             |

# Percentage of equivalence between CFS and steel bar in beam of beam-column connection.
2.4. Steel Preparation

Cold-formed steel plates (CFS) were folded to the required cross section size using a press break machine. To form an opening in the shear zone and the gaps required to affix the steel sections to the steel tubes, a cutting process was using a Computer Numerical Control (CNC) machine. To attain a bond between the beam steel section and the concrete, bolts of 4 mm diameter and 20 mm length (Bolt1) were fixed on the upper flange of the steel section at a distance 100 mm from each other. The cold-formed steel sections were connected by 8 mm diameter bolts of 100 mm length (Bolt2) at the centre of the cold-formed steel sections, in a web along the length of the beam, as shown in Figure 4.

2.5. Casting of Specimens

To create the reference specimen, steel bars were placed appropriately in the mold and cast with normal concrete. For the other specimens, the first step was to fill the vertical steel tubes with normal concrete; then, the cold-form steel plate sections were installed on the tube at specific gaps and the contact areas welded. After 18 to 25 min from casting, the frame (tube and cold-form steel plate sections) was placed horizontally and the steel plate sections put in the appropriate places on the beam mold, before casting beam with normal concrete. More details are shown in Figure 5.

Figure 3. Details of cold-formed steel sections.
Figure 4. Steel Preparation.
3. Test Procedure

A hydraulic universal testing machine with a capacity of 1,000 kN was used to test the beam-column connection, with specimens subjected to point load at each free end of beam as static loads. The testing machine, which was located in the Structural Laboratory of the Faculty of Engineering, Al-Qadisiyah University, included a hydraulic actuator, steel frame, load cell, and computer. C75x40x5x7 mm and two steel plate 40x40x20 mm were used to form the steel structure as a support at end of the column, and welding was applied to connect all elements, as shown in Figure 6. Two linear variable differential transformer (LVDT) were used to estimate the vertical deflection at each free end of the beam. The deflection values were recorded as the load was applied on the beam-column connection.
4. Results and Discussion

The results of the tests described above are discussed in the following sections.

4.1. Cracking and Ultimate Loads and Failure Modes

Table 3 shows the experimental results, including percentage equivalents, ultimate loads and growing percentage as compared with the reference beam-column connection specimen.

| Specimen    | Percentage of equivalence | Pu (kN) ultimate load | \( \frac{Pu(i)-Pu(r)}{Pu(r)} \times 100 \)* |
|-------------|---------------------------|-----------------------|--------------------------------------------|
| N-N-S       | -                         | 117                   | -                                          |
| CF-ST1-S    | 100                       | 179                   | 52.9                                       |
| CF-ST3-S    | 75                        | 140                   | 19.6                                       |
| CF-ST4-S    | 75                        | 147                   | 25.6                                       |

*: Reference N-N-S, i: other specimens.

It is clear from test results that the CF-ST1-S specimen demonstrates that at 100% equivalence in cross section area between cold-formed steel plate and steel bar reinforcement in beams, an increase in the ultimate load of about 52.9% is seen as compared with the N-N-S reference specimen. As a parametric study, the required cold-formed steel cross section area was reduced in CF-ST3-S and CF-ST4-S specimens to 75%; the test results for these show increases in ultimate loads of about 19.6% and 25.6%, respectively, as compared with the N-N-S specimen.

Figure 7 illustrates the load-deflection curves of specimens and Figure 8 shows their cracking patterns and failure modes. The failure mode of beam-column connections using cold-formed plates and steel tubes reinforced with concrete was similar to that of the specimen with conventional bar reinforcement, based on the development of cracks. The cracks formed generally in regions where the tensile stresses exceed the specified tensile strength of concrete. During testing, numerous micro flexural cracks appeared early in the process at the centre of the beam. These cracks were extended and widened as the load increased. Cracks were also observed in the beams in the region of the beam cross-section, above the neutral axis for negative bending moment, due to flexural tensile stresses. The only difference was seen in the width and length of cracks, where the cold-formed steel plates worked to control the crack width and to reduce its length.

![Figure 7. Load-deflection curves](image-url)
4.2. Toughness
The toughness of a material (Ut) is defined as the ability of the material to absorb energy, being related to a combination of strength ductility. More specifically, “Flexure toughness can define as the calculated area under the load deflection curve” [9],[10]. Table 4 illustrates the toughness values for the tested specimens, showing that creating beam-column connections using CFS and steel tubes increased the toughness by about 29.5%, 10.9%, and 15.1% for CF-ST1-S, CF-ST3-S, and CF-ST4-S, respectively as compared with N-N-S (Table 4). This behaviour can be explained by the fact that the steel area has a larger spacing, increasing the maximum load and the area of load deflection curve.

| Specimen     | Toughness (N.m) | \( \frac{T_{00} - T_{r}}{T_{r}} \times 100^\circ \) | Percentage of equivalence |
|--------------|----------------|-------------------------------------------------|--------------------------|
| N-N-S        | 1410           | -                                               | -                        |
| CF-ST1-S     | 1825           | 29.5                                            | 100%                     |
| CF-ST3-S     | 1565           | 10.9                                            | 75%                      |
| CF-ST4-S     | 1623           | 15.1                                            | 75%                      |

* r: Reference N-N-S, i: Another specimen.

5. Conclusion
From the results above, the following conclusions emerge:

1. Cold-formed steel plate can be used to reinforce concrete beams with respect to beam-column connections; the load capacity and toughness are improved due to the increase in the effective area of steel.
2. Local buckling, which is one of the main problems in cold-formed steel plates, is prevented by the encasement of concrete.
3. The strength of concrete is increased due to the confining effect provided by the steel tubes and the cold-formed steel plate sections.
4. Steel tubes filled with concrete can be used to create reinforced columns and connections.
5. Using cold-formed steel plate as a reinforcement offers an improvement the flexure capacity and toughness, with the current results showing an increase in ultimate load by about 19.6 to 52.9% and an increase in toughness by about 10.9 to 29.5% as compared with the reference specimen.

6. The addition of steel plates can control crack width and reduce the length.

6. Reference

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