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### EXPERIMENTAL INVESTIGATION OF CONFINING THE COMPRESSION ZONE IN OVER-REINFORCED BEAMS

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#### ABSTRACT

Over-reinforced concrete sections are restricted in most design codes to avoid the brittle compression failure of concrete, which occurs suddenly without warnings. In recent years, there have been significant improvements in construction industry that needs to use over-reinforced sections in huge projects such as, high-rise building and bridges. In over-reinforced concrete sections, a high percentage of reinforcement steel is added into concrete section to reduce the beam size and to provide adequate stiffness. Limited trials have been carried out to strengthen the over-reinforced section by using proper confinement in the compression zone, which restrains the lateral expansion and failure of concrete at the compression zone. This study investigates experimentally the effect of installing different configurations of confinement in the compression zone of over-reinforced concrete beams. These configurations contain distributed steel bars at the compression zone confined by square ties, circular ties, square spirals, or circular spirals. Six full-scale beams, 3000 mm long and 150×250 mm<sup>2</sup> cross section, were tested under a four-point bending load. The results indicate significant enhancement in the flexural strength, ductility, and failure propagation of the beams especially when using the spiral confinement.

**KEYWORDS:** Beam, Over-reinforced sections, Confinement, Flexural strength, Ductility.

#### INTRODUCTION

Beam is a structural element that carries load primarily in bending. Bending causes the beam to go into compression and tension zones. The compression zone must be designed to resist buckling and crushing, while the tension zone must be able to resist the tension. When designing reinforced concrete beams, designers have to limit the amount of tensile reinforcement to prevent the brittle failure of concrete. Therefore, the full potential of the use of steel reinforcement cannot be achieved. At over reinforced-concrete sections, the longitudinal reinforcement ratio should be allowed to exceed the maximum value specified in design codes by using the confining stirrups in compression zone.

As known, the transverse steel in concrete members serves three functions: (1) confine the concrete section, (2) prevent of lateral buckling of the longitudinal steel, (3) increase of shear resistance. Previous research shows that the brittle failure of over-reinforced beams can be prevented by using transverse steel as confinement in the compression zone [1, 2]. Confining ties can increase the ductility of the over-reinforced beams, but up to a certain limit of volume fraction [3]. The increase in the longitudinal reinforcement ratio increases the strength and ductility of well-confined specimens

with large ratios of lateral reinforcement [4]. Concrete cover spalling off occurs after the beams have reached their maximum load capacity. The confining stirrups delay failure beyond the point at which the cover first begin spalling off [1].

Using over-reinforced confined concrete beams reduce the cross section and the weight of members. Most design codes do not provide design rules for over-reinforced confined concrete beams and there is limited research about their behavior and ductility. It is important that reinforced-concrete members are able to withstand large deformations whilst maintaining strength capacity in situations where. There is a need to withstand significant over loads, by greeting load carrying capacity if adequate confinement can be achieved. For an over-reinforced concrete beam, proper confinement enhances ductility and increases the compressive strength of the confined region. Then, it eliminates the brittle compression failure by restraining the lateral expansion of the compressed concrete. Base and Read [5] showed through experimental testing that the confinement enhances the strength and ductility of a beam contains high tensile longitudinal steel percentage. It has been observed that all most of research concerning confinement of compression zone in beams is based on the result of research on columns. So, more study and data on the behavior of confined concrete beams is needed.

## EXPERIMENTAL PROGRAM

### Beam Specimens

Six full-scale beams, 3000 mm long and 150×250 mm<sup>2</sup> cross section, were tested under a four-point bending load over a simply supported span of 2800 mm.

High tensile ribbed steel bars of 22 mm diameter and yield stress  $f_y$  equals 460 MPa were used as tension steel. In addition, high tensile ribbed steel bars of 10 mm diameter and yield stress  $f_y$  equals 480 MPa were used as compression steel and shear reinforcement for the beams. Mild steel of 8 mm diameter and yield stress  $f_y$  equals 380 MPa were used as confinement reinforcement in the compression zone for the beams.

The control beams (B1 and B2) were designed to fail in compression by using flexural steel reinforcement greater than the balanced steel reinforcement ratio, which is calculated by ACI 318 [6] as:

$$\rho_b = \left( \frac{0.85\beta_1 f'_c}{f_y} \right) \left( \frac{c_b}{d} \right) \quad (1)$$

Where,  $f'_c$  is defined as the cylindrical compressive strength of concrete.  $\beta_1 = 0.85$  for concrete with  $f'_c \leq 27$  MPa.  $f_y$  is the yield stress of tension steel,  $d$  is the depth of the section measured from the top compression fiber to the centroid of the steel bars,  $c_b$  is the neutral axis depth at balanced case.

A balanced strain condition exists at a cross-section when the maximum strain at the extreme compression fiber reaches  $\epsilon_u = 0.003$  simultaneously with the yield strain of  $\epsilon_s = \epsilon_y = f_y/E_s$  at the tension reinforcement. The neutral axis depth at balanced section is given by the following equations:

$$\frac{c_b}{d} = \frac{\epsilon_u}{\epsilon_u + \epsilon_y} \quad (2)$$

$$\frac{c_b}{d} = \frac{0.003}{0.003 + \frac{f_y}{E_s}} = \frac{0.003}{0.003 + \frac{f_y}{200000}} \quad (3)$$

$$\frac{c_b}{d} = \frac{600}{600 + f_y} \quad (4)$$

All the beam specimens have the same concrete dimensions and the same tension reinforcement ratio ( $\rho = A_s/bd = 7.88\%$ ) which is greater than the balanced reinforcement ratio ( $\rho_b = 2.33\%$ ). Where,  $A_s$  is the actual tension reinforcement area,  $b$  is the beam width, and  $d$  is the depth of the section. The main tensile reinforcement for all the beam specimens is 6Φ22 and the shear reinforcement stirrups are 1Φ10 at 100mm spacing. All the beams were casted with the same batch of normal weight concrete. The cylindrical compressive strength of the concrete at 28 days was 25 MPa. The reinforcement details for the beam specimens (B1 to B6) are summarized in Table 1 and represented in Figure 1.

### Test Setup and Instrumentations

Three dial gauges were used below the beam specimens to record the vertical deflection of the beams. The gauges were located at mid-span, 1050 mm and 1750 mm measured from lift edge of beam to get the deflection profile of the beam.

Before casting the specimens with concrete, electrical strain gauges, 10 mm long, 120 ohms resistance, and gauge factor (2.04) were fixed on the steel bars using epoxy at beam the most critical section at mid-span. Then, a wax film was layered on the top of the strain gauge to protect it. The steel strains were measured using a digital strain indicator connected to data acquisition system.

Concrete strains at the beams depth were measured using Demic points. The Demic points were installed at the side of the beams at the mid-span at different rows. The first row was at the top surface of the beams. The second and third rows were at depth 50 mm, 100 mm, respectively, measured from the beams top surface.

The flexural tests were carried out in the reinforced concrete laboratory of the Faculty of Engineering-Elmattaria, Helwan University. The beam was horizontally positioned and rested on two supports, a hinged right support and a roller left support. The supports were fixed on a strong frame. Rigid I.P.E 300 were rested in two rigid bars were centered on the beam to simulate a two-point load on the tested beam. A hydraulic jack of 250 kN capacity was used to load the beam. The load was applied and controlled manually based on the load cell readings. Figure 2 shows a view of the test setup.

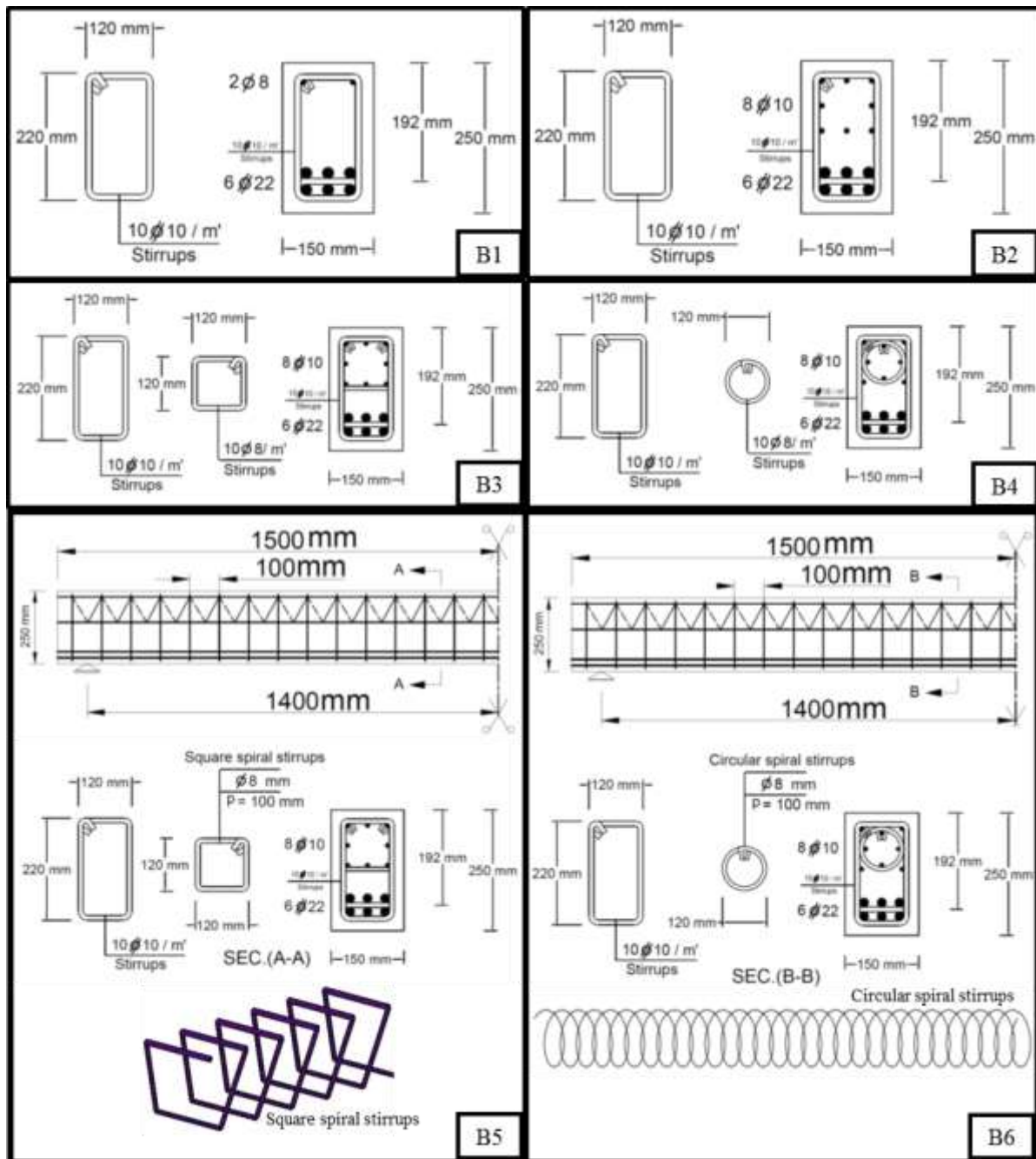
After preparing the test setup and before loading, zero loading of steel strain and vertical concrete displacements recorded and checked. The electrical instrumentation readings were initialized to zero using the testing software of the data acquisition system. Then the load was applied gradually with constant rate of loading 10 kN/min during the test. All data and observations were recorded during the test.

## RESULTS AND DISCUSSIONS

The experimental results are presented in terms of load versus mid-span deflection, load versus steel strains at the compression and tension reinforcement, and strain profile along the beam depth. Table 2 shows a summary of the ultimate failure load and the ultimate mid-span deflection of the six beams

**Table 1: Beam specimens reinforcement details**

Beam	Cross section $b \times d$ (mm)	Tension steel $A_s$	Compression steel $A'_s$	Compression steel ratio $= A'_s / bd$ (%)	$A'_s / A_s$ (%)	Confinement configuration at the compression zone
B1	150x250	6 $\Phi$ 22	2 $\Phi$ 8	0.35	4.38	.....
B2		6 $\Phi$ 22	8 $\Phi$ 10	2.17	27.52	.....
B3		6 $\Phi$ 22	8 $\Phi$ 10	2.17	27.52	10 $\Phi$ 8/m square tied stirrups
B4		6 $\Phi$ 22	8 $\Phi$ 10	2.17	27.52	10 $\Phi$ 8/m circular tied stirrups
B5		6 $\Phi$ 22	8 $\Phi$ 10	2.17	27.52	$\Phi$ 8 square spiral with pitch 100 mm
B6		6 $\Phi$ 22	8 $\Phi$ 10	2.17	27.52	$\Phi$ 8 circular spiral with pitch 100 mm



**Figure 1: Beam specimens' details**

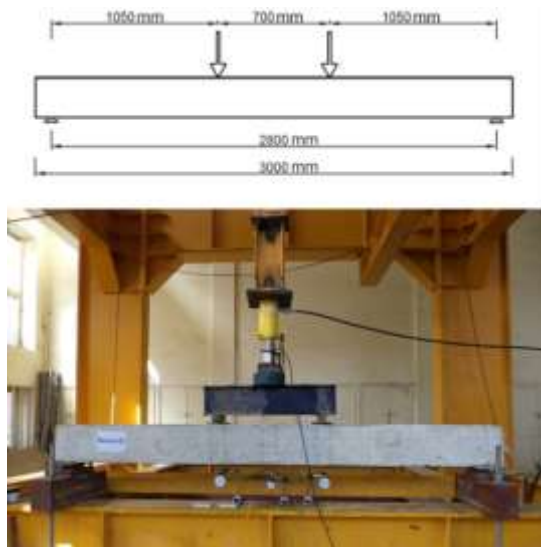


Figure 2: Test setup

**Failure Mechanisms**

Figure 5 show the Failure patterns for all tested Beams. All the beams failed under flexure. Specimens B1, failed in compression by crushing of concrete, because the compression stresses and strains in the concrete top exceeded the maximum allowable compressive stress and strains of concrete. B2 and B3 experienced higher strength and deformation than B1, because of increasing the compression steel. They failed in compression by crushing of concrete and buckling (yielding) of the compression steel. Specimens B4, B5 and B6 failed in tension, because the tension stress in the bottom steel exceeded the yield stress of steel. After yielding, the compression stresses increased until exceeding the maximum allowable compressive stresses and strains of concrete. Due to the high compressive strains and stresses on the top steel bars, buckling of the top reinforcement occurred and the concrete cover spalled off. Therefore, the failure of B4, B5 and B6 can be considered as tension failure followed by compression failure. B5 and B6, which have spiral confinement at the compression zone experienced aggressive compression failure at the end of the test. At this load, the top cover of beam spalled off and the load cell readings dropped slightly, and it was not possible to maintain the load constant because of excessive deflection.

**Load Deflection curves**

Figure 3 plots the load-deflection response of the tested beams (B1 to B6). All deflection curves indicated that all specimens have almost the same profile where the first part of the curves is steep (elastic zone). After cracks, most of profiles started to be different and more curved until the failure occurred (plastic zone).

As expected, using confinement in the compression zone increased effectively the ultimate flexural capacity, ductility and energy absorption of the over-reinforced confined beams B3, B4, B5, and B6

compared to the over-reinforced unconfined beams B1 and B2. For example, confining the compression zone with circular spirals increased the flexural capacity, deflection, and energy absorption of B6 52%, 78%, and 226% higher than that of B1, which has no confinement, respectively.

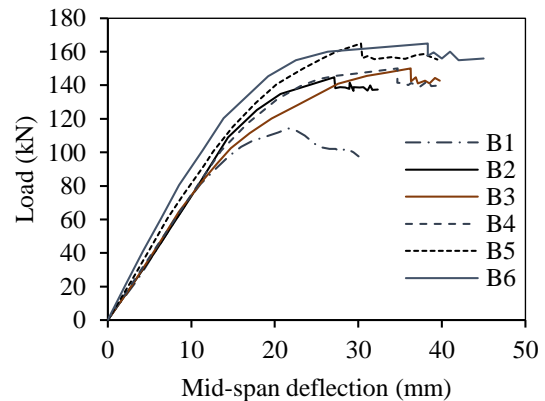


Figure 3: Load- deflection Curves

**Steel Strains**

Figure 4 plots the correlations between the load and the tension steel strains (on the right) and the compression steel strains (on the left). From the steel strain curves, the strain in the bottom steel of B1, B2 and slightly B3 did not reach the yield strain. On other side, the compressive strains indicated yield of the compression steel in B2 and B3. This confirms the compression failure of B1, B2 and B3. While in beams B4, B5 and B6, the bottom and top steel reached the yield strain. It confirms that B4, B5 and B6 failed in tension then in compression. The change in confinement configuration led to changing the failure type from pure compression to tension failure. It means the full potential of using steel reinforcement can be achieved by using proper confinement configuration. Top reinforcement strain was more than the yield strain in all beams. It means full utilization of the compression steel in the over-reinforced section.

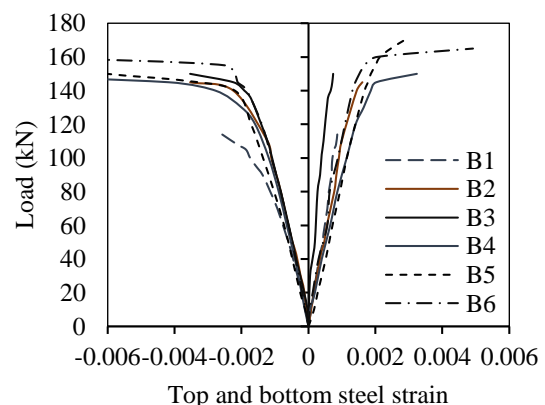
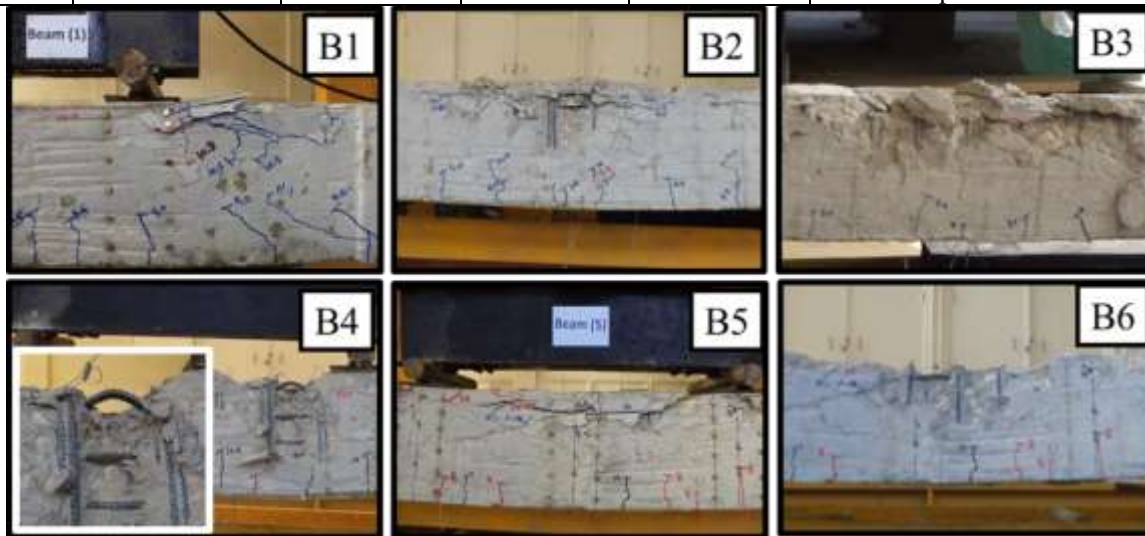


Figure 4: load-Steel Strain Curve

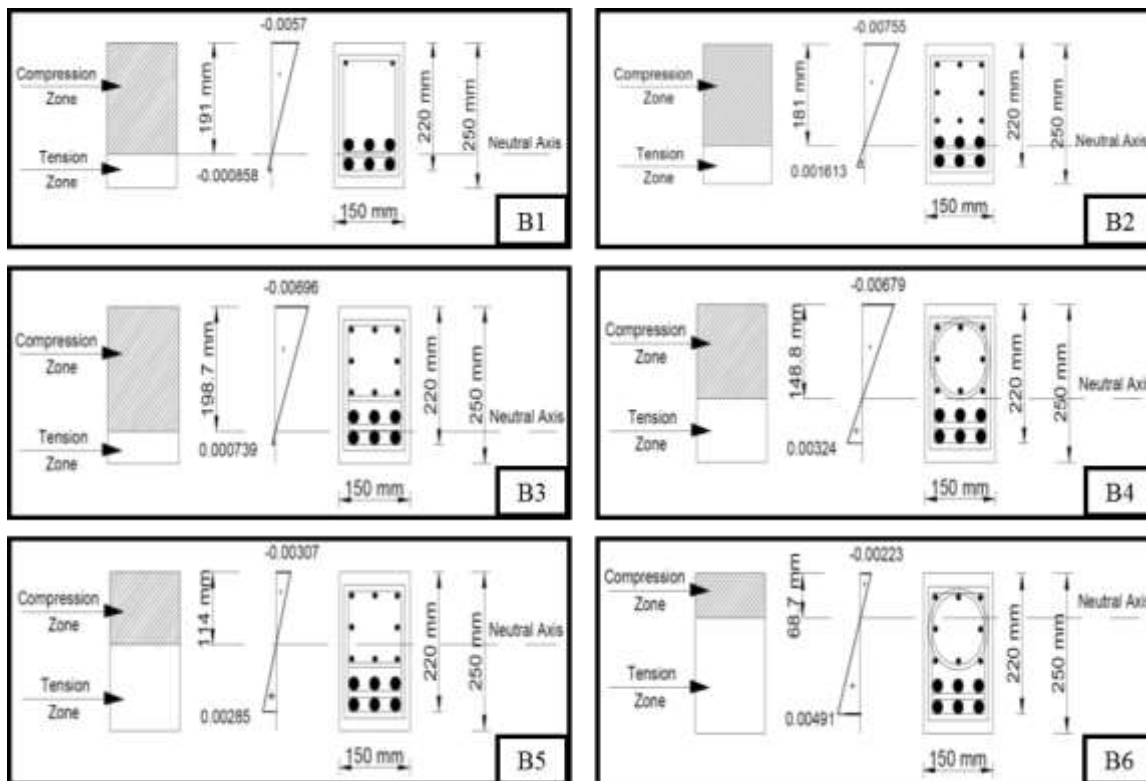


**Table 2: Experimental Results**

Beam	Confinement configuration	Failure Load (kN)	$\Delta_{max}$ at mid-span (mm)	Energy absorption (kN.mm)	Type of Failure
B1	without	116	21.5	1419	Compression failure
B2	without	146	27	2423	Compression failure
B3	Square ties	153	36.2	3644	Compression failure
B4	Circular ties	155	34.6	3546	Tension failure followed by Compression failure
B5	Square spiral	175	34.7	3875	Tension failure followed by Compression failure
B6	Circular spiral	176	38.2	4623	Tension failure followed by Compression failure



**Figure 5: Patterns of failure**



**Figure 6: Strains and neutral axis location**

**Neutral Axis Location**

Location of the neutral axis can be determined from the strains along the cross section of the beam. Using the strain values from the Demic points that records the concrete strains, and the steel strains from the strain indicator, to draw the strain profile along the cross section. Figure 6 shows the strains and the location of the neutral axis for the tested beams. The compression zone covered about 76.4%, 72.4% and 79.48 % from B1, B2 and B3 cross sections, respectively. It confirms that B1, B2 and B3 failed in compression. The results of B4, B5 and B6, which have confinement at the compression zone, indicated reduction in the compression zone area and the neutral axis moved up. The compression zone area covered about 73.92%, 45.6% and 27.48% from B4, B5 and B6 cross sections, respectively. It means using proper confinement configuration change the failure mode from compression failure as B1, B2 and B3 to tension failure as B4, B5 and B6. The neutral axis location shows the efficiency of using confinement in compression zone, especially the circular spirals, to achieve the full potential of tension and compression reinforcement steel.

**Effect of Uniform Distribution of Compression Steel in the Compression Zone**

The test specimens B1 and B2 had the same concrete dimensions, tension reinforcement and shear reinforcement, but differed in the percentage and distribution of the compression reinforcement  $\rho'$ , which equal 4.4% from the tension reinforcement placed in the top fiber of compression zone in B1 and 27.5% from the tension reinforcement distributed uniformly in the compression zone in B2. B1 ( $\rho' = 4.4\%$  from the tension reinforcement) failed in a brittle flexural mode because the area of tension reinforcement larger than the area of reinforcement required for balanced failure. Where, the concrete crushing appeared suddenly in the top surface of the Beam and ran through the beam depth. As the compression reinforcement percentage increased, in B2, the brittle mode began to decrease. B2 ( $\rho' = 27\%$  from the tension reinforcement) also failed in brittle flexural mode but more ductile than B1. Where, the concrete crushing appeared in the top surface of the Beam and ran through the Beam depth. The concrete cover of the steel at the compression side spalled off at the end of test. Generally, it was noticed that, with increasing the compression steel percentage, the failure load and deformability (ductility) increased. The results indicate that B2 had flexure capacity, ultimate deflection, and energy absorption 26%, 26%, and 71% higher than B1, respectively. The strain curves of B2 indicate yielding of compression steel. However, the strain of the bottom steel did not reached the yield where the compression failure took place. This means, the tension reinforcement does not resist the applied loads with its full capacity.

**Effect of Confining the Compression Zone with Square Ties**

The specimen B3 presents this studied parameter. The behaviour of B3 is approximately similar to B2. The results indicate that B3 had flexure capacity, ultimate deflection, and energy absorption 5%, 34%, and 50% higher than B2, respectively. As seen, there is enhancement in ductility. However, there is minor enhancement in strength. It means, the square confinement have small effect in enhancing the flexural capacity. Also, the square confinement configuration did not achieve the target to change the compression failure to tension failure. This result matches the common low confinement efficiency of the square columns.

**Effect of Confining the Compression Zone with Circular Ties**

The specimen B4 presents this studied parameter. The behaviour of B4 is different from B2. Circular confinement configuration changed the failure type from compression to tension failure. It is observed in the yielding of bottom reinforcement, (see Figure 4). This means, the tension reinforcement resists the applied loads with its full capacity. Then, the top reinforcement yielded causing buckling of steel and spalling off the concrete cover (compression failure). The results indicate that B4 had flexure capacity, ultimate deflection, and energy absorption 6%, 28%, and 46% higher than B2, respectively. The results are similar to that of B3. However, the circular confinement configuration changes clearly the compression failure to tension failure.

**Effect of Confining the Compression Zone with Square Spirals**

The specimen B5 presents this studied parameter. The behavior of B5 is compared to B3. The bottom reinforcement of B5 yielded and a tension failure took place. The flexure capacity for B5 increased and the failure type changed from compression failure to tension failure. In addition, the top reinforcement reached to the yielding. Buckling of the compression steel happened and the concrete cover spalled off as B4. The results indicate that B5 had flexure capacity, ultimate deflection, and energy absorption 13%, 1%, and 10% higher than B4, respectively. Note that, the results indicate also that B5 had flexure capacity, ultimate deflection, and energy absorption 20%, 29%, and 60% higher than B2, respectively. Square spiral confinement configuration changed the compression failure to tension failure and increased significantly the flexural capacity and ductility.

**Effect of Confining the Compression Zone with Circular Spirals**

The specimen B6 presents this studied parameter. B6 is compared to B5 that have the same behavior.

The results indicate that B6 had flexure capacity, ultimate deflection, and energy absorption 14%, 10%, and 30% higher than B4, respectively. Note that, the results indicate also that B6 had flexure capacity, ultimate deflection, and energy absorption 21%, 42%, and 91% higher than B2, respectively. Circular spiral confinement configuration changed the compression failure to tension failure and increased significantly the flexural capacity and ductility. Note that, B6, which is over-reinforced confined with circular spiral, experienced the highest flexural performance of the tested beams in this study.

## CONCLUSIONS

The main conclusions of this study concerning the effect of confining the compression zone in over-reinforced concrete beams can be summarized as follows:

- 1) Significant increase in the flexural capacity and ductility can be achieved when confining the compression zone in over-reinforced beam section. In addition, the compression failure of over-reinforced beams can be prevented.
- 2) The ACI 318 [6] value of  $\rho_{max} = 0.75 \rho_b$  is too restrictive. It is possible to increase this limit if proper confinement is provided in over-reinforced beam section.
- 3) Confining the compression zone with square and circular spiral indicated superior efficiency and performance in terms of flexural capacity, deformability, and energy absorption.
- 4) More analysis and experimental investigations are required to study well the confinement configuration in the compression zone of over-reinforced beam. The parameters of the pitch and the spiral diameter need more investigations.

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