Influence of steel fibers on the behavior of spirally RC short columns

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Abstract. This study provides an experimental test to examine the behavior of spirally reinforced short columns with circular sections, strengthened by steel fibers. The volume percentage of steel fibers was (0.5, 1.0, 1.5) %. Four series comprising a total of 16 column specimens (600 mm length × 150 mm diameter) were loaded to failure under axial concentric compression load. The findings of this work are as follows: for the control specimens (columns without steel fibers), the spiral pitch influence was significant: as compared to spiral pitch of 100 mm, reducing the spacing to 75 mm, 50 mm, and 25 mm increased the ultimate load capacity by 7.6%, 11.5% and 18.4%, respectively. The steel fibers effect was very significant in increasing the ultimate load capacity of the columns. For 100 mm spiral pitch columns, these increases reached to 24.6%, 36.3% and 49.9% for the columns with 0.5%, 1.0% and 1.5% steel fibers volume percentages, respectively in comparison to the control specimen. The columns with lesser amount of spirals (less internal confinement) were strengthened by the steel fibers more than the ones with greater number of spirals. For 1.5% steel fibers volume percentage, the column with 100 mm spiral pitch was strengthened by 49.9% with steel fibers. In contrast, the one with 25 mm spiral pitch increased in strength with steel fibers by 41.4%.

Keywords: Load carrying capacity, RC short columns, Spiral pitch, Steel fiber reinforced concrete.

1. Introduction

Columns are among the most important elements of a structure that their failure can lead to the destruction of the whole building [1]. They are classified as short and slender columns. The short ones have the load carrying capacity at a given eccentricity governed by the cross sectional dimensions and the strength of the materials only. Circular reinforced concrete (RC) column sections have been used in the projects of civil engineering, particularly in bridge pier columns. These sections are used to resist traffic loads, wind loads, lateral shocks, braking forces and lateral earth pressure [2].

Using steel fibers improves the ductility of concrete under all modes of loading [3]. The addition of steel fibers to the columns leads to improvements in tension stiffening and crack control in addition to decrease the lateral strain [1].

The present study provides an experimental work for the spirally reinforced normal strength concrete circular short columns strengthened with steel fibers. The objectives of this work are: (1) the effect of the variation of transverse reinforcement volumetric ratio (spiral pitch) on the carrying capacity of spirally reinforced short columns; and (2) the steel fibers effect on the columns carrying capacity.
2. Experimental work
A total of 16 RC column specimens with 150 mm diameter circular section and 600 mm height were tested in this program. A concrete cover of 15 mm was used in all tested specimens and between the longitudinal bar ends and the upper and lower column surfaces to restrain the effect of direct loading on the bars.

Depending on the spiral pitch (100, 75, 50, and 25) mm, the specimens were separated into four groups; each group consists of four specimens with steel fibers volume percentages of (0, 0.5, 1, 1.5) %. Six longitudinal bars of 6 mm diameter and spiral of 4 mm diameter were used to reinforce all specimens. Figure 1 shows the details of the spirally reinforced columns.

![Figure 1. Details of the spirally RC columns.](image)

3. Column specimen identification
For each group (four columns), the first one (Type A) is a control column (without steel fibers). The second one (Type B) is strengthened by 0.5% steel fibers. The third one (Type C) is strengthened by 1% steel fibers. While the fourth one (Type D) is strengthened by 1.5% steel fibers.

Letters and numbers are used to identify the column specimens. The letter (S) represents the spiral column. The numbers (100, 75, 50 and 25) refer to the spiral pitch (in mm). The letters (A, B, C and D) indicate the column type according to the steel fibers volume percentage. For example (S-50-B) refers to a spirally RC column with 50 mm spiral pitch and the volume percentage of steel fibers is 0.5%.

4. Construction materials
4.1. Cement
The cement used in this work is ordinary Portland cement (Type I) manufactured in Iraq by Al-Mass Company. The chemical and physical properties meet the Iraqi specification No.5/1984 [4].

4.2. Fine aggregate
The fine aggregate used throughout this experimental work is AL-Ukhaider natural sand with max. size of 4.75 mm. The fineness modulus, specific gravity, absorption, and sulfate content of this fine aggregate are in agreement with the Iraqi standard specification No.45/1984 [5].

4.3. Coarse aggregate
Natural gravel with max. size of 10 mm is used in this research. The gravel was washed, exposed to the air for surface drying. The coarse aggregate grading is in agreement with the requirements of the Iraqi standard specification No.45/1984 [5].

4.4. Water
Tap water from the network system is used for mixing and curing all the specimens.

4.5. Rebars
Two sizes of deformed bars are used for all column specimens. For longitudinal reinforcement, 6 mm diameter steel bars are used with yield stress of 452 MPa. While the transverse reinforcement (spiral) bar diameter is 4 mm with 656 MPa yield stress.

4.6. Steel fibers
In this test program, straight steel fibers are used in accordance with ASTM A 820/A 820M - 04 [6]. The mechanical properties of Steel fibers are given in table 1 according to the manufacturing specifications.

| Description                        | Micro copper coated straight steel fiber |
|-----------------------------------|-----------------------------------------|
| Density                           | 7800 kg/m³                              |
| Tensile strength                  | 2850-3000 MPa                           |
| Diameter                          | 0.2 mm                                  |
| Length                            | 15 mm                                   |
| Aspect ratio                      | 75                                      |

Table 1. Mechanical properties of steel fiber.

*a: Provided by the manufacturer.

5. Trial mixes
A number of mixes are performed to obtain cylindrical concrete compressive strength more than 30MPa. For this study, trial mix No. (4) was adopted. Table 2 shows trial mixes details.

| Trial No. | Cement (kg/m³) | Sand (kg/m³) | Gravel (kg/m³) | Water (kg/m³) | Water/cement ratio | Mixing ratio (by weight) | Compressive strength (MPa) |
|-----------|----------------|--------------|----------------|---------------|--------------------|--------------------------|----------------------------|
| 1         | 330            | 780          | 922            | 205           | 0.62               | 1:2.36:2.79              | 20.0                       |
| 2         | 370            | 685          | 1020           | 189           | 0.51               | 1:1.85:2.76              | 27.3                       |
| 3         | 390            | 685          | 1075           | 183.5         | 0.47               | 1:1.76:2.76              | 28.5                       |
| 4         | 400            | 740          | 1000           | 192           | 0.48               | 1:1.85:2.50              | 30.8                       |

6. Mixing procedure
The concrete mixes are performed in a rotary mixer of 0.1 m³ capacity. Cement, fine and coarse aggregate are mixed for 5 minutes, water is added in quarters and leaves all components to mix for additional 3 minutes. Steel fibers are distributed slowly into the mixture in five minutes (to avoid balling), then the mixing is continued for 3 more minutes to get a homogeneous concrete paste.

7. Specimen molds
PVC tubes are used as molds to cast the column specimens. They are cut to the appropriate height of column. To prevent water leak from the molds, their bases are constructed from plywood.

8. Casting and curing
To cast the column specimens, four batches of concrete mixes were used. Four columns and their control specimens (to find the mechanical properties of concrete) were cast from each batch. These control specimens include: 3 cylinders of (100×200) mm for concrete compressive strength ($f'_c$) according to ASTM C 39/C 39M – 05 [7]; 3 cubes of (100×100×100) mm for concrete compressive strength ($f_{cu}$) according to B.S: 1881: part 116 [8]; 3 cylinders of (100×200) mm for concrete splitting tensile strength ($f_{sp}$) according to ASTM C 496/C 496M - 04 [9]; and 3 prisms of (100×100×400) mm for concrete flexural strength ($f_r$) according to ASTM C 78 - 02 [10].

Steel reinforcement was placed in the column molds. Then the columns were cast and vibrated with three layers by using an electrical vibrating table to consolidate and remove the air bubbles from each layer. Plastic sheets were used to cover all the specimens to avoid the cracks of shrinkage. Specimens were demolded after 24 hours from casting, and placed in water tanks for 28 days of curing.

9. Spirally reinforced columns test
A testing machine (Avery) of 2500 kN at the laboratory of structures of the civil engineering department is used for column specimens testing by applying monotonically compression load. A total of 8 demec points and 2 dial gauges were used for each column. The lateral displacement was measured by using a dial gauge fixed at the mid height of the column specimen, while the other gauge was fixed at the machine bottom surface, which is rising during the testing process to measure the column axial shortening. Four demec points fixed at each opposite face of the specimen were used for the strain computations; two of them were placed at the column mid height along the horizontal axis to measure the column lateral strains, while the other two demec points were fixed at the specimen mid height on the vertical axis to measure the specimen longitudinal compressive strains. Two steel collars of 10 mm thickness and 50 mm height were used to confine both ends of each column.

The columns were tested under compression loading up to the failure. The readings of the dial gauges, lateral strains and longitudinal strains were recorded until the column failure for each increment of loading as shown in plate 1.
10. Control specimens
The control specimens were tested immediately after the columns test. Table 3 shows the control specimens test results.

| Column type | Steel fibers (%) | Compressive strength $f'_c$ (MPa) | Compressive strength $f_{cu}$ (MPa) | $f'_c / f_{cu}$ | Splitting tensile strength $f_{sp}$ (MPa) | Modulus of rupture $f_r$ (MPa) |
|-------------|------------------|----------------------------------|-------------------------------------|----------------|----------------------------------------|-----------------------------|
| A           | 0.0              | 31.20                            | 37.34                               | 0.836          | 3.19                                   | 3.98                        |
| B           | 0.5              | 33.54                            | 40.41                               | 0.830          | 3.67                                   | 5.77                        |
| C           | 1.0              | 35.06                            | 41.82                               | 0.838          | 3.80                                   | 6.13                        |
| D           | 1.5              | 37.01                            | 44.42                               | 0.833          | 4.08                                   | 6.45                        |

ACI 544.1R [3] indicates that the concrete compressive strength increases up to 15% for 1.5% volume percentage of steel fibers. The experimental results of compressive strength of this work are almost consistent with this indication. It also indicates that the flexural strength of steel fiber reinforced concrete is about 50% to 70% more than that of the concrete without steel fibers. Tensile strengths of concrete can be increased by using steel fibers that would prevent the microcracks propagation, thereby delaying the tension cracks onset and increasing the concrete tensile strength [2]. The ACI 544.4R [11] indicates that the flexural strength is typically in the range of (5.5 to 7.5) MPa for concretes containing (0.5 to 1.5) % volume percentage of steel fibers, respectively. The experimental flexural strength results of this study are compatible with these indications.

11. Axial load capacity for the tested column specimens
Table 4 and figure 2 show the tested results for the columns ultimate load capacity.
The spiral pitch influence was significant as can be seen from the experimental results. In comparison with 100 mm spiral pitch, reducing the spacing to (75, 50, 25) mm increased the column load carrying capacity by (7.6, 11.5, 18.4) %, respectively, for the control column specimens. The corresponding values of increase for 0.5%, 1.0% and 1.5% volume percentages of steel fibers were (5.4, 7.5, 12.5) %, (5.9, 8.0, 12.9) % and (5.2, 7.8, 11.7) %, respectively. Reducing of spiral pitch led to an increase in the load carrying capacity for the columns without steel fibers more than the ones with steel fibers. For example, dropping the spiral pitch from 100 mm to 25 mm increases the ultimate load carrying capacity by 18.4%.

### Table 4. Experimental and calculated results for the columns ultimate load capacity.

| Column designation | Experimental axial load capacity $P_{exp}$ (kN) | Calculated axial load capacity $P_{cal}$ (kN) | $P_{exp} / P_{cal}$ | Spiral pitch influence | Steel fiber influence |
|--------------------|-----------------------------------------------|-----------------------------------------------|---------------------|------------------------|-----------------------|
|                    |                                               |                                               |                     | Column designation     | Ultimate load increase (%) |
| S-100-A            | 503.88                                        | 540.81                                        | 0.932               | S-100-A                | 11.69                 |
| S-75-A             | 542.12                                        | 540.81                                        | 1.002               | S-75-A                 | 7.59                  |
| S-50-A             | 561.74                                        | 540.81                                        | 1.039               | S-50-A                 | 11.48                 |
| S-25-A             | 596.48                                        | 540.81                                        | 1.103               | S-25-A                 | 18.38                 |
| S-100-B            | 627.84                                        | 575.62                                        | 1.091               | S-100-B                | 5.19                  |
| S-75-B             | 661.90                                        | 575.62                                        | 1.150               | S-75-B                 | 5.42                  |
| S-50-B             | 674.89                                        | 575.62                                        | 1.172               | S-50-B                 | 7.49                  |
| S-25-B             | 706.32                                        | 575.62                                        | 1.227               | S-25-B                 | 12.50                 |
| S-100-C            | 686.70                                        | 598.23                                        | 1.148               | S-100-C                | 5.89                  |
| S-75-C             | 727.15                                        | 598.23                                        | 1.216               | S-75-C                 | 5.89                  |
| S-50-C             | 741.83                                        | 598.23                                        | 1.240               | S-50-C                 | 8.03                  |
| S-25-C             | 774.99                                        | 598.23                                        | 1.295               | S-25-C                 | 12.86                 |
| S-100-D            | 755.37                                        | 627.24                                        | 1.204               | S-100-D                | 5.19                  |
| S-75-D             | 794.61                                        | 627.24                                        | 1.267               | S-75-D                 | 5.19                  |
| S-50-D             | 814.23                                        | 627.24                                        | 1.298               | S-50-D                 | 7.79                  |
| S-25-D             | 843.66                                        | 627.24                                        | 1.345               | S-25-D                 | 11.69                 |

**Figure 2.** Experimental results for the columns ultimate load capacity.
load capacity by 18.4% for the control column. The corresponding increase for 1.5% volume percentage of steel fibers was 11.7%.

Using of steel fibers is very effective to increase the columns ultimate load capacity. These increases were (24.6, 36.3, 49.9) % for 100 mm spiral pitch strengthened with steel fibers volume percentages of (0.5, 1.0, 1.5) %, respectively. The corresponding increases for 75mm, 50mm and 25mm spiral pitch were (22.1, 34.1, 46.6) %, (20.1, 32.1, 45.0) % and (18.4, 29.9, 41.4) %, respectively, for the same steel fibers volume percentages. The column specimens with 100 mm spiral pitch (lesser number of spirals) were reinforced by the steel fibers more than 25 mm spiral pitch (greater number of spirals) as shown in table 4. For 1.5% steel fibers volume percentage, the ultimate load capacity of the column with 100 mm spiral pitch was increased by 49.9%. In contrast, the one with 25 mm spiral pitch was increased by 41.4%.

To predict the theoretical values of columns ultimate load capacity, equation (1) of ACI 318M-14 [12] for the spirally reinforced columns is used (neglecting the reduction factors):

\[ P = 0.85 f_c' (A_g - A_{st}) + f_y A_{st} \]  

(1)

Where \( P \) is the maximum axial compressive load, \( f_c' \) is the compressive strength of concrete, \( A_g \) is the column gross cross sectional area, \( A_{st} \) is the longitudinal reinforcement area, and \( f_y \) is the yield stress of longitudinal reinforcement.

According to the provisions of ACI 318M-14 code [12], the limits of spiral pitch range between 25 mm to 75 mm. It can be seen from table 4 that the calculated values (\( P_{\text{cal}} \)) were smaller than the experimental ones (\( P_{\text{exp}} \)) for all the column specimens except for the control column (S-100-A). This column has 100 mm spiral pitch, which is greater than 75 mm - the upper limit of the ACI 318M-14 code [12]. Although that the spiral pitch of the columns (S-100-B, S-100-C and S-100-D) was out of the ACI code limits, they gave safe experimental results because the steel fibers improve the ductility of concrete under all modes of loading and leads to improvements in tension stiffening and crack control in addition to the decrease in the lateral strain of the columns and delay in their failure. Therefore, the ACI 318M-14 code [12] requirements for the spiral pitch of the spirally reinforced columns without steel fibers can be used for spirally reinforced columns strengthened by steel fibers even with spiral pitch values that exceed slightly the upper limit of the code. Also, it can be noticed from table 4 that the factor of safety of the tested results increases with a decrease in the spiral pitch values.

12. Failure shape

All columns were investigated by applying a concentric compression load until failure. The control columns - type (A) exhibited linear behavior at the beginning; the first crack was initiated at the mid height of the column at about 55% of its maximum load. At higher loading, the cracks were developed in width and increased in number at the center location along the column’s length. Finally, the concrete cover swelled due to the buckling of longitudinal steel bars and segregated at the mid height area of the column. Then, the rupture of steel spiral occurred. Plate 2 shows the failure shape for the control specimens. It can be seen that the concrete cover for all these columns was spalled.
Plate 2. Failure shapes for the control columns - (type A).

For the columns strengthened with steel fibers, the first crack was initiated at the mid height surface of the column. The cracks developed further at higher loading. Finally, the columns failed by concrete crushing and buckling of one or more of longitudinal steel bars. For the heavy spiral (S-25), it was noticed that the rupture of the internal steel spiral occurred without buckling of longitudinal steel bars. Plates 3 to 5 show the failure shapes for the columns type (B, C and D).

Plate 3. Failure shapes for the columns - (type B).

Plate 4. Failure shapes for the columns - (type C).
13. Load - displacement behavior of spirally RC columns

Figure 3 shows the influence of load-longitudinal displacement on the ultimate load capacity for the control columns (without steel fibers). It can be seen that there is a difference between the control columns behavior, the column with 25 mm spiral pitch leads to an improvement in longitudinal displacement reducing and resulting in an increase the load carrying capacity. Also, there is a lateral displacement reduction with a decrease in the spiral pitch of the columns as shown in figure 4.

Figures (5 to 8) show the influence of load-longitudinal displacement on the load carrying capacity for the (100, 75, 50 and 25) mm spiral pitch columns with different volume percentages of steel fibers. There is a significant effectiveness between the columns in comparison with the control specimens. The longitudinal displacement was reduced with the increase in the steel fibers volume percentages. Therefore, the lateral displacement will be reduced too; resulting in an increase in the ultimate load capacity of the columns as indicated in figures (9 to 12).
Figure 5. Load - longitudinal displacement for 100 mm spiral pitch columns.

Figure 6. Load - longitudinal displacement for 75 mm spiral pitch columns.

Figure 7. Load - longitudinal displacement for 50 mm spiral pitch columns.

Figure 8. Load - longitudinal displacement for 25 mm spiral pitch columns.

Figure 9. Load - lateral displacement for 100 mm spiral pitch columns.

Figure 10. Load - lateral displacement for 75 mm spiral pitch columns.
14. Conclusions
Based on the experimental investigation of this work, the following conclusions are made:

1. The concrete compressive strength ($f'_c$) and the modulus of rupture ($f_t$) were increased by 18.6% and 62.1%, respectively for concrete with 1.5% steel fibers volume percentage in comparison with concrete without steel fibers.
2. For the columns without steel fibers, the spiral pitch influence was significant. In comparison with 100 mm spiral pitch, reducing the spacing to (75, 50, 25) mm increased the column load carrying capacity by (7.6, 11.5, 18.4) %, respectively.
3. Reducing of spiral pitch increased the load carrying capacity for the columns without steel fibers more than the ones with steel fibers. For example, dropping the spiral pitch from 100 mm to 25 mm increases the ultimate load capacity by 18.4% for the control column. The corresponding increase for 1.5% steel fibers volume percentage was 11.7%.
4. Using of steel fibers with the RC columns is very effective to increase the columns ultimate load capacity. The increases were (24.6, 36.3, 49.9) % for 100 mm spiral pitch strengthened with steel fibers volume percentages of (0.5, 1.0, 1.5) %, respectively. The corresponding increases for 25mm spiral pitch were (18.4, 29.9, 41.4) % for the same steel fibers volume percentages.
5. The column specimens with 100 mm spiral pitch (lesser number of spirals) were reinforced by the steel fibers more than 25 mm spiral pitch columns (greater number of spirals). For 1.5% steel fibers volume percentage, the ultimate load capacity of the column with 100 mm spiral pitch was increased by 49.9%. On the other hand, the increase was 41.4% for 25 mm spiral pitch column.
6. The calculated values ($P_{cal}$) were smaller than the experimental ones ($P_{exp}$) for all the column specimens except for the control column S-100-A (spiral pitch is greater than the upper limit of the ACI code).
7. The ACI 318M-14 code [12] requirements for the spiral pitch of the spirally reinforced columns without steel fibers can be used for spirally reinforced columns strengthened by steel fibers even with spiral pitch values that exceed slightly the upper limit of the code, because the steel fibers improve the ductility of concrete and lead to improvements in tension stiffening and crack control in addition to decreasing the lateral strain of the columns and delaying their failure.
8. The ratio of the experimental values of load carrying capacity to the calculated ones ($P_{exp}/P_{cal}$) i.e. the factor of safety increases with a decrease in the spiral pitch value and increase in steel fibers volume percentage.
9. For the columns strengthened with steel fibers, the columns failed by concrete crushing and buckling of one or more of longitudinal steel bars. For the heavy spiral (S-25), it was noticed that the rupture of the internal steel spiral occurred without buckling of longitudinal steel bars.

10. For the same load, the increase in volume percentage of steel fibers led to a decrease in the longitudinal displacement and mid-height lateral displacement of the spirally reinforced columns.

15. References

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