Experimental and numerical investigation of the effect of cross-section shape on damaged self-compacting concrete columns

Sadjad A. Hemzah 1, Wajde S. Alyhya 1, Basel A. Hassan 1, 2
1 Department of Civil Engineering, University of Kerbala
2 Corresponding Author: basil.a@s.uokerbala.edu.iq

Abstract: This paper experimentally and numerically (using the finite element analysis) examines cross-section shape effects on damaged SCC short columns enhanced with CFRP sheet wrapping. The impact of various strengthening techniques on the structural behaviour of columns was investigated, with the convergence between the experimental and numerical results verified numerically in ABAQUS. The experimental strengthening process included partial or full wrapping in CFRP sheets, with specimens in the first group enhanced with three or five CFRP sheets of 100 mm width and those in the latter group enveloped in CFRP sheet to the full column height. The numerical results agreed well with the experimental results and demonstrated that the square cross-section SCC short column exhibited higher strength capacity than other shapes.

Keywords: ABAQUS; CFRP laminate; SCC; Strengthening; Square.

1. Introduction

Several techniques have been used to enhance the strength capacity of columns, including jacketing, near-surface mounted (NSM), steel strips, and carbon fibre reinforced polymer (CFRP) laminate jacketing [1]. Multiple experimental works have clarified the impact of various strengthening techniques on damaged and undamaged columns. Sarfraz [2] illustrated the effect of reinforcement techniques utilising NSM-CFRP and CFRP laminate jacketing of for columns produced by standard vibrated concrete, while Waleed et al. [3] showed that transverse strengthening with CFRP jacketing was more effective than longitudinal strengthening and that the effectiveness of CFRP jacketing decreased with increases in the eccentricity ratio. Ruili et al. [4] illustrated the impact of external jacketing with CFRP on damaged normal vibrated concrete columns especially when primary bars were used, while in 2016, Hasan et al. [5] demonstrated the efficiency of an enhancement technique with CFRP jacketing that offered excellent performance with regard to crack appearance and reductions to tensile stress. Jain et al. [6] studied the impact of near-surface
mounting of carbon fibre reinforced polymer strips (NSM-CFRP strips) covered by CFRP jacketing on damaged standard normal vibrated columns in addition to other techniques, with results that showed that the techniques examined could restore the original strength capacity of the columns. Chellapandian and Prakash [6] determined that a NSM-CFRP technique improved the strength capacity of columns under an increase in eccentricity, in addition to confirming high efficiency of a strengthening technique utilising NSM-CFRP strips covered by CFRP jacketing under constriction for eccentric loading of columns. Noroozieh [7] used the finite element method to illustrate numerically that increasing the CFRP layers increased the strength capacity to a specific point, after which adding a new layer made no difference as well as determining that increasing both the concrete compressive strength and the steel ratio increased the ultimate load capacity for columns, and that using GFRP laminate instead of CFRP laminate may be preferred for economic reasons. Obaidat [8] created a numerical analysis model using ABAQUS to investigate the impact of increasing the number of CFRP laminate layers and reducing the spacing between them for columns strengthened with partial CFRP jacketing, concluding that increasing the number of CFRP laminate layers and reducing the spacing between them increased the strength capacity for columns enhanced with the technique.

This paper examines the effect of strengthening damaged self-compconsidered concrete (SCC) columns with jacketing in CFRP laminate, in addition to creating a finite element model (FEM) using ABAQUS 2019 to verify the behaviours of partially damaged SCC short columns enhanced with full and partial jacketing of CFRP laminate. Strengthening techniques comprising full or partial jacketing in CFRP laminate were thus applied to improve the structural behaviour of damaged columns, and the effect of changing the geometry of these columns to rectangular and circular sections instead of square ones was then examined using the verified numerical model.

### 2. Experimental Work

Four SCC short columns with identical characteristics were prepared and designed based on ACI 318-19 [9] with a square cross-section of 100 mm and 800 mm height. The primary steel reinforcement involved was four-bar Ø10 mm, while the stirrups were distributed with a spacing of 100 mm along the height of the column. All specimens were tested under compression loading. One of the four SCC columns was loaded to failure and considered as a control column (see figure 1), while the other columns were loaded to 62 % of their ultimate loads or the appearance of the first crack for these columns. The partially loaded columns were then enhanced with part or full CFRP laminate jacketing, as shown in Table 1.

| Specimens symbol | Strengthening process                        |
|------------------|----------------------------------------------|
| CC               | No strengthening                             |
| CFRP3            | Three 100 mm CFRP sheets in three positions  |
| CFRP5            | Five 100 mm CFRP sheets in five positions    |
| CFRPF            | Full jacketing of CFRP                      |
2.1 Wrapping with CFRP laminate

Three SCC short columns were loaded to 62% of their ultimate loads, which offered the appearance of the first crack for these columns. The specimens were then strengthened by the addition of CFRP laminate jacketing, with the corners of the specimens rounded to avoid stress concentration on the laminate at these positions. Sika Warp®-300 laminate was cut to the required length for each strengthening technique. The laminates were placed on the column faces using sikadur-330 epoxy, and an additional layer of epoxy was used to ensure strong bonding between the laminate and the concrete. Figure 2 illustrates the partial and fully jacketing with CFRP laminate, with the partial jacketing presented in specimen CFRP3 (three sheets of CFRP of 100 mm width, distributed at three places (top, middle, and bottom of the column)) and CFRP5 (five sheets of CFRP of 100 mm width spread equally along the column’s height). Full jacketing with CFRP laminate was used to strengthen the CFRPF specimen. All strengthened specimens were then left to dry for five days before testing.
Figure 2. Details of the CFRP jacketing for the columns.

2.2 Strength Capacity and Ductility of Test columns

The structural behaviours for the partially damaged SCC short columns of square cross-section were improved for both full and partial wrapping with CFRP laminates. The partial wrapping increased the strength capacity for the columns, to 440 and 505 kN for specimens CFRP3 and CFRP5, respectively, as compared with the control column (405 kN), as shown in table 2, while the ductility for these specimens increased to 1.54 and 1.57, respectively. Full wrapping with CFRP laminates increased both the strength capacity and ductility index, to 550 kN and 1.60, respectively. The increases in ultimate capacity and ductility index increment of the strengthened columns occur due to the effects of confinement caused by the CFRP laminates, which enhances the structural behaviour of partially damaged columns.

Table 2. Results for tested columns.

| Column symbol | Ultimate strength \((f_u)\) kN | Ultimate displacement \((\Delta u)\) mm | Yielding strength \((f_y=0.8\times f_u)\) kN | Yielding displacement \((\Delta y)\) mm | Ductility index \(DI=\Delta u/\Delta y\) | Ultimate load ratio % |
|---------------|-------------------------------|--------------------------------------|---------------------------------------------|--------------------------------------|------------------------------------------|----------------------|
| CC            | 405                           | 2.750                                | 324                                         | 2.066                                | 1.33                                     | -                    |
| CFRP3         | 440                           | 3.250                                | 352                                         | 2.100                                | 1.54                                     | 08.64                |
| CFRP5         | 505                           | 4.100                                | 404                                         | 2.600                                | 1.57                                     | 24.69                |
| CFRPF         | 550                           | 4.370                                | 440                                         | 2.602                                | 1.67                                     | 35.80                |
3. **Numerical Study**

3.1 **Material Modelling**

The materials used in the FEM for these columns included concrete, steel reinforcement (primary and transverse reinforcement), and CFRP laminate. All elements in the analysis were meshed with a mesh size of 15 mm, with results of 393.74 kN and 2.85 mm for the ultimate strength capacity and maximum displacement, respectively. These figures are very close to the experimental results for the control column (405 kN, 2.75 mm).

3.1.1. **Concrete**

All columns were modelled with square cross-sections of 100 mm and 800 mm height. The concrete was modelled as a solid brick element to achieve effective stress distribution in the 3D analysis of finite elements. The concrete compressive strength and Young’s modules for the model were 40 MPa and 30,725 MPa, respectively. Figure 3 presents the model of the stress-strain relationship used in this research.

3.1.2. **Steel Rebars**

Two types of steel rebars were used in each specimen, a 4 Ø8 mm bars as the main rebar, with one in each corner of the specimen, and Ø6 mm @50 mm and @100 mm as stirrups at the ends and other key positions. The steel rebar was embedded inside the concrete in specific regions, and the Poisson ratio and modulus of elasticity were 0.3 and 200 MPa, respectively.

3.1.3. **CFRP laminates**

Specimens were enhanced with CFRP laminate jacketing with a thickness of 0.167 mm. At the modelling stage, the lamina option was selected with respect to elastic behaviour to simulate the laminate and to allow it to be treated as a shell element. The tie constrain was chosen to create a bond between the CFRP laminate and the surface of the concrete, and the dry fibre modulus of elasticity in tension and dry fibre tensile strength for the laminates were 230,000 and 3,500 MPa, respectively.
3.2. Verification Study

The control column and the columns strengthened with CFRP jacketing were modelled and analysed in ABAQUS (Standard 2019). Figure 4 presents the convergence between the experimental and the numerical results for the load–vertical deflection curves, in which the deflection is measured at the centre of the column from the upper side. The results show reasonable convergence between the numerical and experimental results, confirming the validity of the model.

A comparison was made between the experimental and numerical results in terms of ultimate load and maximum displacement for each specimen. The mean differences in the ultimate load and maximum displacement for the tested columns as shown in Table 3 were 3.90 and 4.16%, respectively. This demonstrates that the numerical simulation in ABAQUS (Standard 2019) offers reliable output for assessing experimental work.
Figure 4. Load-deflection curves for the tested columns.
Table 3. Experimental and numerical results for the tested columns.

| Specimen symbol | Ultimate Load (Pu) kN | Different percentage in ultimate load % | Maximum Deflection (Δu) mm | Different percentage in displacement % |
|-----------------|-----------------------|----------------------------------------|-----------------------------|----------------------------------------|
| EXP CC          | 405                   | 2.86                                   | 2.75                        | 3.64                                   |
| EXP CFRP3       | 440                   | 4.68                                   | 3.25                        | 6.15                                   |
| EXP CFRP5       | 505                   | 3.97                                   | 4.10                        | 3.18                                   |
| EXP CFRPF       | 550                   | 4.10                                   | 4.37                        | 3.66                                   |
| Mean Value      |                       | 3.90                                   | 4.16                        |                                        |

3.2.1 Effect of Cross Section Shape

The parametric investigation involved changing the column cross-sections to rectangular and circular cross-section instead of the square section in the experimental work. Other column properties, such as percentages of steel rebars and the number of the CFRP layers, were kept constant. After changing the cross-section of the modelled column to a rectangular or circular shape, similar strengthening techniques were applied as in the first experiments. Figure 5 shows the changes made in the cross-section of the columns (square, rectangular, and circular).

3.2.1.1 Rectangular Section

The dimensions for the rectangular column were 125 mm length, 80 mm width, and 800 mm height. A similar strategy was adopted in the numerical work as for the square section column, in which one column was tested to failure and thus considered as a control column, while the other columns were damaged to 62% of their ultimate load, then enhanced with the relevant strengthening techniques, including three sheets of CFRP (CFRP3), five sheets of CFRP (CFRP5), and full jacketing in CFRP (CFRPF). The results showed that the strength capacity of the rectangular section decreased to 370 kN in CC specimens in comparison with the CC with a square-section. However, the strengthened rectangular specimens (CFRP3, CFRP5, and CFRPF) exhibited higher strength capacities, with values of (400.56, 452.37, and 550.38) kN respectively,
as compared with the CC for the rectangular section, as shown in Table 4. Figure 6 illustrates the load-deflection curves for CFRP3, CFRP5, and CFRPF specimens with rectangular sections.

| Square-Section | Rectangular-Section | Circular-Section |
|----------------|---------------------|------------------|
| 100 mm x 100 mm | 80 mm x 125 mm      | D=112.83 mm      |

![Figure 5. Column geometries.](image)
### Table 4. Results for rectangular sections columns enhanced with CFRP wrapping

| Column symbol | Strength capacity kN | Increment Ratio % | Max. Deflection mm |
|---------------|-----------------------|-------------------|--------------------|
| CC            | 375.62                | ........           | 2.45               |
| CFRP3         | 400.56                | 6.64              | 2.63               |
| CFRP5         | 452.37                | 20.43             | 2.89               |
| CFRPF         | 550.38                | 46.53             | 3.61               |

![Figure 6. Load-deflection curves of CFRP3, CFRP3, and CFRPF for the column of rectangular cross-section.](image-url)
3.2.1.2 Circular Section

A circular cross-section with a 112.83 mm diameter and 800 mm height was also utilised, as shown in Figure 3. The same process was followed for the circular section as for other sections, in which one specimen was loaded to failure to develop a control column while the other specimens were loaded partially to 62% and then strengthened with the same CFRP techniques. The results showed that using the circular cross-section reduced the strength capacity of the control column to 356.48 kN. However, the full and partial strengthening techniques utilising CFRP as implemented in specimens CFRP3, CFRP3, and CFRPF increased the strength capacity to values of (388.35, 436.24, and 527.13) kN, respectively (see Table 5). Figure 7 illustrates the load-deflection curves for CFRP3, CFRP5, and CFRPF with circular sections.

| Column symbol | Strength capacity kN | Increment Ratio % | Max. Deflection mm |
|---------------|----------------------|-------------------|--------------------|
| CC            | 356.48               | ........           | 2.21               |
| CFRP3         | 388.35               | 8.91              | 2.56               |
| CFRP5         | 436.24               | 22.37             | 2.82               |
| CFRPF         | 527.13               | 47.87             | 3.45               |
4. Conclusions

Based on the experimental and numerical results, the following conclusions can be drawn:

1. Full and partial jacketing with CFRP laminate for partially loaded SCC square cross-section columns was found to improve the structural behaviour of the columns; the specimen with full CFRP jacketing recorded an increment in strength capacity of 35.8%, while the specimens with partial jacketing (CFRP3 and CFRP5) recorded increments of (8.64 and 24.69) %, respectively, in comparison with the CC for the square section.

2. Good agreement between the experimental and numerical results was obtained, with the mean differences observed in terms of the ultimate load and maximum deflection being 3.90 and 4.16%, respectively.

3. The strength capacities of the columns with rectangular sections were lower than that of the square section columns, where the moment of inertia for the rectangular section with the least dimensions was lower than that of the square section, giving reductions in strength capacity for CC, CFRP3,
CFRP5, and CFRPF with rectangular sections of (4.60, 4.71, 6.67, and 3.87) %, respectively as compared with the equivalent square columns.

4. The strength capacities of the columns with circular sections were lower than those with square and rectangular sections due to the moment of inertia for the circular sections being less than those in the square sections; the decreases in strength capacity for the CC, CFRP3, CFRP5, and CFRPF samples with circular sections were (9.46, 7.61, 10.19, and 7.93) %, respectively, in comparison with the square sections.

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