Numerical Investigation for the Structural Behaviour of Different Strengthening Techniques for Partially-Loaded Square Self-Compacted Concrete Short Columns

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This paper aims to study numerically the structural behaviour of partially loaded square SCC short columns strengthening with various techniques such as near-surface mounted with steel reinforcement bars (NSM), CFRP wrapping, and both of them (hybrid technique). For this purpose, the results of the ultimate strengths and complete load-deflection response of strengthened columns investigated experimentally in an under-publishing paper were used to verify the accuracy of the computational results. Additional parameters were examined thoroughly the numerical work, such as the effect of extra CFRP layers, the effect of various compressive strengths, the effect of changing initial loading ratios, and the effect of various numbers of CFRP strips. Results showed that the numerical investigation recorded an excellent agreement with the experimental work through the convergence in the value of both the ultimate load and maximum displacement. Furthermore, increasing the layers of CFRP laminate was active in the specimens strengthened with full CFRP wrapping and hybrid one. The same effect occurred as the compressive strength of the column increased. Rising the loading ratio caused a decrease in the strength capacity for the columns. In contrast, decreasing the spacing between two successive laminates increased the ultimate load capacity for the specimens enhanced partially wrapping with CFRP laminate.

Keywords: ABAQUS; Numerical study; strengthening; SCC; CFRP laminate.

I. Introduction

In general, column is considered as one of the essential elements in structural buildings, which transfers loads from slabs and beams to the foundations. Columns in construction buildings may expose to natural disasters like a storm or earth quick, or they could be designed according to old specifications[1]. Such situations and others could prevent columns from resisting applied loads. Therefore, these columns require strengthening using various techniques like wrapping of CFRP laminate, near-surface mounted (NSM) with steel bars, jacketing technique, strengthening using steel strips ties, or combination of some of these methods [2]. Several experimental research
demonstrated the efficiency of these techniques on damaged and undamaged normal vibrated concrete columns such as those given in [3], [4], [5]. Furthermore, numerical investigations were thoroughly implemented to simulate the experimental results, or to study other new parameters that could not be studied experimentally. Chellapandian [6] showed a good convergence between the experimental and numerical results when strengthening columns with NSM-CFRP, CFRP wrapping, and both. The author concluded that increasing the percentage of NSM-CFRP strip improved the columns load capacity under comparison loads. Noroozieh [7] performed a numerical analysis by ABAQUS for the experimental results carried out by sarafraz [8]. Besides, the author investigated other parameters such as the effect of changing the number of CFRP layers, increase the steel reinforcement diameter, use GFRP instead CFRP, and the impact of concrete compressive strength. From the obtained results, the author found out that there were optimal numbers for the CFRP layers in which any additional layers would not make a difference. Increasing the steel ratios and the compressive strength led to an increase in the columns load capacity. Obaidat [9] built up a finite element model using ABAQUS program for specimens enhanced with partially CFRP wrapping and compared with other specimens prepared previously. In addition, the author study the effect of decrease the spacing between CFRP laminate and the effect of changing the number of the layers of CFRP laminates. The author concluded that decreasing the spacing between CFRP laminates and increasing the layers of CFRP laminates led to an increase in the ultimate load capacity of the columns.

This paper aims to create a numerical model based on experimental data from an under-publishing paper carried out by the authors upon nine partially damaged SCC squared short cross-section columns. Where one column loaded to the failure and consider as a control column and other columns loaded to 0.62 of the ultimate load then strengthening with the mentioned techniques. Also, the author aims to investigate from the verified numerical model additional parameters including studying the effect of increasing CFRP layers, the impact of changing the concrete compressive strength, increasing initial loading ratio, and the effect of reducing the space between two successive CFRP laminates.
II. Material Modelling

The materials used in modelling of columns (Details of the columns of the experimental work was shown in Table 1) included concrete, steel reinforcement (primary and transverse reinforcement and NSM rebar), steel plates, filling materials (epoxy), and CFRP laminate.

1. **Concrete**

All specimens have the same square cross-section of 100 mm in side and 800 mm in height, as shown in Figure 1. The concrete was modelled as a solid brick element to achieve a suitable distribution of stress in a 3D analysis of finite elements, which is taken from [10]. The compressive strength for SCC columns as mentioned in experimental data. The general properties of the used concrete are illustrated in the Table 2.

2. **Steel reinforcement**

Two types of steel reinforcement were used in each model: 4 Ø8 mm for the primary reinforcement (one at each corner) and Ø6 mm @50 mm and Ø6 mm @100mm for the transverse reinforcement, at the ends and other positions, respectively (Figure1). The steel reinforcement was embedded inside the concrete using embedded region constrain. The modulus of elasticity and Poisson's ratios were 200 MPa and 0.3, respectively.

3. **Steel plates**

Two steel plates were used at the top and bottom of the model with dimensions of (200×200×20) mm for length, width, and thickness, respectively. The elastic modulus and Poisson's ratios for the plates were 200 GPa and 0.3, respectively. The plates were connected to the surfaces of the concrete by tie constrain, as shown in Figure1.

4. **CFRP laminate**

All specimens were strengthened by wrapping a 0.167 mm CFRP, as given in Table 1. At the modelling, lamina option in the elastic behaviour was chosen to simulate the laminate and treated as shell element and it is bonded to the concrete by using tie constrain. All CFRP properties are clarified in Table 3.
5. Filling materials and NSM rebar

Strengthening specimens with NSM technique included a filling material (epoxy) and NSM rebar. The filing material was presented as a brick element with a cross-section of \((12 \times 12) \text{ mm}^2\) or \((14 \times 14) \text{ mm}^2\) based on the NSM rebar size along the total height of the specimens (800 mm), as shown in Figure 1. Tie constrain was used to bond the filling material with the concrete. Table 4 showed the general properties of the filling material. NSM rebar consisted of Ø8 mm and Ø10 mm, which embedded inside the filling material using embedded region constrain.

![Fig. 1. The materials used (A) Concrete and steel plates (B) Steel reinforcement (C) CFRP laminate (CFRP5 specimen) (D) Filling materials with the concrete](image-url)
Table 1. Details of the specimens of the experimental work

| Group number | Specimens designation | Strengthening scheme                           |
|--------------|-----------------------|------------------------------------------------|
| Control column | CC                   | No strengthening                                |
| Group 1      | CFRP3                 | Three 100 mm CFRP strips in three positions     |
|              | CFRP5                 | Five 100 mm CFRP strips in five positions       |
|              | CFRPF                 | Full wrapping of CFRP                           |
| Group 2      | CN4D8                 | 4Ø8 NSM rebar, one bar each face               |
|              | CN4D10                | 4Ø10 NSM rebar, one bar each face              |
|              | CN8D8                 | 8Ø8 NSM rebar, two bar each face               |
|              | CN8D10                | 8Ø10 NSM rebar, two bar each face              |
| Group 3      | CN4D10F               | Full wrapping of CFRP with one Ø10 NSM rebar in each face |

Table 2. General properties used in the model for the concrete

| Dilation angle | Eccentricity | Fb0/fc0 | k   | Viscosity parameter | Young modules | Poisson Ratio |
|----------------|--------------|--------|-----|---------------------|---------------|---------------|
| 40             | 0.1          | 1.16   | 0.667 | 1E-07               | 30725         | 0.18          |

Table 3. Properties of CFRP laminate

| Material | Dry Fiber Modulus of Elasticity in Tension (MPa) | Dry Fiber Tensile Strength (MPa) | Laminate Nominal Thickness (mm) |
|----------|-------------------------------------------------|----------------------------------|--------------------------------|
| CFRP     | 230 000                                         | 3500                             | 0.167                          |

Table 4. Properties of filling materials (epoxy) [11]

| Material | Compressive strength (MPa) | Tensile Strength (MPa) | Young modules (MPa) |
|----------|----------------------------|------------------------|---------------------|
| Epoxy    | 80                         | 30                     | 3800                |
6. Meshing

A convergence study was conducted in this paper to determine the best density that gives the desired accuracy, which was the reason behind using various element sizes in ABAQUS. Table 5 lists the ultimate loads capacity obtained for each element size. It can be observed that the ultimate load and deflection value obtained for element size 15 mm was almost 393.74 KN, 2.85 mm, respectively. These values are very close to the results obtained from the experimental results (405 KN, 2.75 mm). Thus, element size of 15 mm was selected in this paper.

| Element size | Ultimate load | Maximum deflection |
|--------------|---------------|--------------------|
|              | KN            | mm                 |
| Exp          | 405.0         | 2.75               |
| FEA          | 393.7         | 2.85               |
| Exp          | 417.5         | 2.90               |
| FEA          | 427.8         | 2.92               |
| Exp          | 466.9         | 2.95               |
| FEA          | 471.2         | 3.07               |
III. Finite element analysis results and discussion

1. The verification study

All columns strengthened with various techniques (Table 1) were modelled and analyzed using ABAQUS software. Figure 2 presented a comparison between the experimental and the numerical results of load-vertical deflection curves, where the deflection is measured at the top of the column. The validity of numerical results can be obtained from Fig. 2, which showed functional convergences with the experimental results.
Fig. 2. The experimental and numerical curves for the columns
A comparison was being done between the results of the ultimate load and the maximum deflection obtained from the experimental work with those obtained from the numerical analysis by ABAQUS. It can be concluded from Table 6 that the experimental and numerical results were in a strong convergence. The mean difference values in load capacity and maximum deflection were 2.75 and 4.36 %, respectively. This can ensure that the numerical simulation by ABAQUS could constitute a valid output for the experimental work.

Table 6. The experimental and numerical results

| Groups | Specimen symbol | Ultimate Load (Pu) kN | Different percentage in ultimate load | Maximum Deflection (Δu) mm | Different percentage in displacement |
|--------|-----------------|-----------------------|--------------------------------------|-----------------------------|------------------------------------|
| Group 1 | EXP 405 | 2.86 | 2.75 |
| FEA 393.74 | 2.85 |
| CN4D8 | EXP 420 | 2.31 | 3.015 |
| FEA 410.52 | 3.10 |
| CN4D10 | EXP 425 | 1.33 | 2.956 |
| FEA 430.64 | 3.054 |
| CN8D8 | EXP 320 | 1.58 | 2.015 |
| FEA 315.036 | 2.15 |
| CN8D10 | EXP 340 | 1.4 | 2.198 |
| FEA 335.24 | 2.37 |
| CFRP3 | EXP 440 | 4.68 | 3.25 |
| FEA 420.34 | 3.45 |
| CFRP5 | EXP 505 | 3.97 | 4.10 |
| FEA 485.72 | 4.23 |
| EXP 550 | 4.37 |
2. Parametric study

Several essential parameters were investigated numerically by the verified ABAQUS to examine their effect on the behaviour of partially damaged SCC columns under concentrated loads. These parameters included increasing the number of CFRP layers, the effect of concrete compressive strength, the impact of changing the initial loading ratio, and the effect of reducing the spacing between CFRP sheets.

2.1. Increasing number of CFRP layers

Increasing the layers for the specimens of CFRP3, CFRP5, CFRPF, and CN4D10F to two and three layers instead of one layer was investigated. Results showed that this parameter improved the ultimate load slightly for the specimens strengthening with partially wrapping. In contrast,
the specimens enhanced with full wrapping of CFRP gained an excellent increment in the ultimate load capacity when changing the number of layers from one layer to two or three layers. The increment ratios were (16.58, 29.89)% and (23.21, 37.48)% respectively when increasing the layers to two and three layers for the mentioned specimens in comparison with the specimens of one layer. Load-deflection curves for these specimens illustrated in figure 3.

1.1. Influence of Compressive strength
This parameter was investigated by changing the compressive strength of concrete (i.e. 25, 35, 45, and 55) MPa for CFRPF and CN4D10F specimens. Observing Figure 4, it can be concluded that increasing the compressive strength led to an increase in the ultimate load capacity. Increasing the compressive strength from 40 to 55MPa increased the ultimate load capacity of CFRPF and CN4D10F by (27.54, 22.97)% respectively. Figure 4 illustrates the load-vertical deflection curves for those specimens.

1.2. The effect of increasing initial loading ratio
In order to investigate the effect of this parameter on the specimen behaviour enhanced with various strengthening techniques, the loading initial ratio of the ultimate load changed from 62% to (65, 70, 75, and 80)% for the specimen of CC and CFRPF, which consider as important cases in comparison with other cases. The obtained results showed that the ultimate load capacity decreased as the loading ratio increases. Increasing the loading ratio from (0.62-0.8) decreased the ultimate load capacity for the specimens of CC and CFRPF to (9.20, 6.52)% respectively. Figure 5 showed the curves of the load-vertical displacement of CC and CFRPF specimens.
Fig. 4. The effect of the compressive strength on the load-vertical deflection curves of CFRPF, and CN4D10F
1.3. Reducing the space between two successive CFRP laminate

This parameter was investigated on CFRP3 and CFRP5 specimens, which enhanced partially with CFRP wrapping. For this, the spacing was decreased from 250 mm (CFRP3 specimen) to 133.33 mm (CFRP4 specimen), and from 75 mm (CFRP5 specimen) to 40 mm (CFRP6 specimen). The reduction in the space between CFRP laminate (in other words, increase the slices of CFRP laminate) led to an increase in the strength capacity of the column. Where the increment in the strength capacity of the columns of CFRP4 and CFRP6 reached to 450.62, and 532.53 compared with CFRP3 and CFRP5. Figure 6 presented the curve of load-vertical deflection for the partially wrapping specimens.

Fig. 5. Loading ratio influence on the load-vertical deflection curves of CC and CFRPF

Fig. 6. Load-vertical deflection curve for the specimens of CFRP3, CFRP4, CFRP5, and CFRP6
IV. Conclusion

1. The results of the ultimate load capacity and maximum deflection between the numerical and experimental results of all columns were excellently matched, which can support the validity of the results obtained from the numerical solution.

2. Increasing the number of CFRP layers was very useful in improving the strength capacity of the specimens strengthened with full CFRP wrapping and hybrid technique. The increments were (16.58, 29.89) % and (23.21, 37.48) %, respectively when using two or three layers for CFRPF and CN4D10F respectively.

3. Increasing the concrete compressive strength improved the ultimate load capacity for the strengthening columns, where the increment in the ultimate load occurred in CFRPF and CN4D10F were (27.54 and 22.97) %, respectively.

4. Opposite relationship between the strength capacity and the loading ratio was obtained as increasing the loading ratio from 62% to 80% decreased the strength capacity for the columns.

5. Reducing space between two successive CFRP laminate led to an increase in the ultimate load capacity for the columns partially strengthening with CFRP wrapping.

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