BEHAVIOR OF CONCRETE COLUMNS REINFORCED WITH LONGITUDINAL FIBER REINFORCED PLASTIC BARS

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Abstract
Using FRP material due to their excellent features like high strength to weight ratio, resistance to corrosion, convenience of transportation and installation, is developing rapidly. Using FRP bar instead of steel rebar significantly prevent corrosion in concrete members specifically for seashore concrete structures.

In this research, in order to investigate the benefits of replacing steel rebar with FRP bars in concrete columns, some column specimens were modeled in finite element computer program and the effects of parameters like FRP bar ratio and compressive strength of concrete on the flexural capacity and ductility of column were discussed. The investigations on the concrete columns strengthened with CFRP bar and steel rebar, indicates that the FRP bar ratio is significantly less than the steel rebar ratio to achieve the acceptable strength.

Keywords: Compressive strength of concrete, concrete column, flexibility, flexural capacity, FRP bar ratio.

1. Introduction
Near-surface mounted (NSM) fiber-reinforced polymer (FRP) reinforcement is one of the latest and most promising strengthening techniques for reinforced concrete (RC) structures. The NSM FRP technique is an attractive way of increasing the flexural and shear strength of deficient RC members [1][2].

This technique was successfully used to upgrade the flexural capacity of reinforced concrete (RC) piers. Flexural strengthening and testing to failure of the piers were carried out on a bridge that was scheduled for demolition during the spring of 1999. Three of the four piers of the bridge were strengthened with different configurations using FRP rods and jackets. The flexural strengthening was achieved using NSM carbon FRP rods that were anchored into the footings [3].

The first systematic study on NSM-based flexural strengthening of RC columns under simulated seismic loading was presented by Bournas and Triantafillou [4]. Their investigation addressed column strengthening with NSM carbon or glass fibers, as well as stainless steel rebars. Another innovative aspect in that study was the combination of NSM reinforcement with local jacketing, which comprised the recently developed textile-reinforced mortar (TRM) confining system, described by Triantafillou et al. (2006) and Bournas et al. (2007) [5][6].
The obtained experimental results from a recent study by Barros et al. (2008) involved strengthening RC columns subjected to axial compression and lateral cyclic loading with NSM CFRP strips indicate that the proposed strengthening technique is very promising for increasing the load carrying capacity of concrete columns failing in bending. However, as was expected, the energy absorption capacity of the tested RC columns was not improved by this technique, since it did not provide significant concrete confinement. [7]

This paper will review the research conducted on replacing steel rebar with CFRP bars in concrete columns to prevent corrosion phenomenon. In order to reach this goal, a three dimensional model of column reinforced with CFRP bar subjected to monotonic lateral with constant axial compressive load was modeled in finite element program and the results obtained from analysis compared to results of experimental work on the same specimen[8][9]. After verification analytical and experimental results, steel reinforcement in concrete columns replaced by CFRP bar and the effect of parameters such as longitudinal CFRP reinforcement ratio and concrete strength on base shear force and ultimate displacement of columns were then investigated. Afterward the equivalent CFRP bar ratio needed to replace steel rebar to reach the same column strength was found.

2. Specimens modeling in finite element program

In order to investigate the accuracy of analytical model, a three dimensional model of a concrete column with cross section of 400 cm^2 (20x20cm) which was reinforced by CFRP bars, was created in finite element program and the force-displacement curves obtained from analysis were compared to the results obtained from experimental work on the same specimen[10]. Afterward columns with cross sectional dimensions of 40x40cm in which steel rebar were replaced by CFRP bar were modeled in computer program and their behavior under axial and lateral load were studied. The geometry, element properties, material specifications, loading and boundary condition are explained in following sections.

2.1 Geometry of Specimens

Geometry of the column which was verified by experimental observation is depicted in Figure 1 and Figure 2. The height of column is 100 cm. The foundation and cap beam were also modeled to apply the boundary condition and loads (Figure 2). This column was strengthened with four NSM CFRP bars (with diameter of 12mm) at each side of it.
Figure 1. Geometry of modeled specimen (dimensions in mm).

Figure 2. Cross sections of cap beam, column and foundation (dimensions in mm)

The column specimens designed to investigate the effects of replacing steel rebar with CFRP bars have cross sectional dimensions of 40x40cm and were reinforced with CFRB bars and steel stirrups. The stirrups were arranged such that all FRP bar placed in the corners. Figure 3 shows the cross section of the specimens.
2.2 Element Properties and Material Specifications

According to the three-dimensional modeling of the specimens, the column, foundation and cap beam were modelled with 3D continuum elements (8-node linear brick element - C3D8). Rebar and stirrup were modelled using truss elements (3-node quadratic displacement elements - T3D2) which were embedded in concrete elements.

Concrete damaged plasticity material model was applied to concrete elements for the assessment of the structural stability and damage of concrete columns subjected to cyclic lateral loading. It assumes that the main two failure mechanisms are tensile cracking and compressive crushing of the concrete material. The evolution of the yield (or failure) surface is controlled by two hardening variables, $\varepsilon^{cr}_{pl}$ and $\varepsilon^{cp}_{pl}$ (which refers to tensile and compressive equivalent plastic strains), linked to failure mechanisms under tension and compression loading, respectively. The material properties used in this study are summarized in Table 1.

Linear kinematic hardening model which is a bilinear model for steel was assumed for steel rebar and stirrup.

CFRP rebar were supposed to have linear elastic behavior up to failure. The rupture strain of CFRP is 1.7%. [11].

Table 1. Summary of material properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Compressive strength (MPa)</th>
<th>Yield strength (MPa)</th>
<th>Elasticity modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>400</td>
<td></td>
<td>200000</td>
</tr>
<tr>
<td>CFRP rebar</td>
<td>2000</td>
<td></td>
<td>72</td>
</tr>
</tbody>
</table>

2.3 Boundary Condition and Loading

Foundation and cap beam of the specimen with cross sectional dimensions of 20x20cm, were also modeled to approximate boundary condition and loading of the experimental work, so that the increasing lateral load applied to the middle of cap beam and the boundary condition was applied to nodes on the bottom of the foundation to constrain the motion of the foundation in the x, y and z-directions as well as the experiment.

A constant axial compressive load of 200 kN (which corresponds to an axial load ratio of
0.25) was applied on the top elements of cap beam in the area of 200x200 mm. This was followed by a monotonic lateral displacement load applied to the cap beam.

![Figure 4](image1.png)

Figure 4. Column with sectional dimensions of 20x20 cm created in computer program

For parametric study specimen columns with cross sectional dimensions of 40x40 cm, were modeled and the bottom elements of columns restrained in all degrees of freedom. Constant axial compressive load of 800 kN (which corresponds to an axial load ratio of 0.25) and monotonic lateral displacement load were applied on the top elements of columns.

![Figure 5](image2.png)

Figure 5. Column with sectional dimensions of 40x40 cm created in computer program

3. **Analytical models**

In order to verify the computer modeling and analytical results, the Control specimen which was described before, was modeled in finite element program and subjected to the lateral and axial load [12]. The experimental observation on this specimen is also available from previous studies [11].

The following denominations are adopted for the specimens designed for parametric studies. Fc(m)- f or s (n) in which “m” refers to concrete compressive strength, “f” or “s” shows if the column reinforced with longitudinal steel rebar(s) or FRP rebar(f) and the diameter of rebar placed instead of (n).
3.1 Verification

Since the cyclic lateral load was applied to the column in experimental work and in this study the column subjected to monotonic lateral load, the base shear force-displacement curve obtained from finite element program compared with envelope of base shear force-displacement curve of experimental work.

![Figure 6. Base shear force-displacement curves obtained from finite element program and experimental work](image)

As it can be seen from the graph the initial stiffness of two curves are very close to each other and also the softening branches are similar. Moreover the comparison between analytical and experimental curves indicates that the values of maximum base shear force differ 4.35% in two curves and the corresponding displacement values differ 3.97%. It can be concluded from above graph that finite element model was successfully verified by experimental results.

Since the aim of this paper is to investigate behavior of columns reinforced by CFRP bars instead of steel rebar, it is recommended that the analytical model verify by the same experimental sample (without steel rebar) in future surveys. But here due to lack of such a specimen, results in this section will suffice.

3.2 Effect of FRP bars ratio on concrete columns behavior

In order to observe the effect of CFRP bars percentage on columns behavior, six column specimens with the same compressive strength of concrete and different CFRP bars ratio were modeled. The columns specifications can be seen in the table below.

<table>
<thead>
<tr>
<th>specimen</th>
<th>Section dimension (cmxcm)</th>
<th>Height of column(m)</th>
<th>CFRP bar percentage(%)</th>
<th>compressive strength of concrete (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>fc20-f4</td>
<td>40x40</td>
<td>1</td>
<td>0.09</td>
<td>20</td>
</tr>
<tr>
<td>fc20-f6</td>
<td>40x40</td>
<td>1</td>
<td>0.21</td>
<td>20</td>
</tr>
<tr>
<td>fc20-f8</td>
<td>40x40</td>
<td>1</td>
<td>0.38</td>
<td>20</td>
</tr>
<tr>
<td>fc20-f10</td>
<td>40x40</td>
<td>1</td>
<td>0.59</td>
<td>20</td>
</tr>
<tr>
<td>fc20-f12</td>
<td>40x40</td>
<td>1</td>
<td>0.85</td>
<td>20</td>
</tr>
<tr>
<td>fc20-f14</td>
<td>40x40</td>
<td>1</td>
<td>1.15</td>
<td>20</td>
</tr>
</tbody>
</table>

The base shear force-displacement curves obtained from analysis are depicted in Figure 7.
As shown in the figure above, increasing the ratio of CFRP bars enhanced column strength and also increased the ultimate displacement of columns (ultimate displacement occurred when strain in CFRP bars reached to rupture strain).

### 3.3 Effect of Concrete Strength on Behavior of Concrete Columns Strengthened with FRP Bars

In order to investigate the effect of concrete compressive strength on columns behavior, four column specimens with the same CFRP bars ratio and different concrete compressive strengths were modeled. The column specifications are shown in the table 3.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Section dimension (cmxcm)</th>
<th>Height of column (m)</th>
<th>CFRP bar percentage (%)</th>
<th>Compressive strength of concrete (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>fc20-f8</td>
<td>40x40</td>
<td>1</td>
<td>0.38</td>
<td>20</td>
</tr>
<tr>
<td>fc30-f8</td>
<td>40x40</td>
<td>1</td>
<td>0.38</td>
<td>30</td>
</tr>
<tr>
<td>fc40-f8</td>
<td>40x40</td>
<td>1</td>
<td>0.38</td>
<td>40</td>
</tr>
<tr>
<td>fc50-f8</td>
<td>40x40</td>
<td>1</td>
<td>0.38</td>
<td>50</td>
</tr>
</tbody>
</table>

The results obtained from analysis can be compared in figure 8.

![Figure 7. Base shear force-displacement curves of specimens with different CFRP bar percentages](image)

**Figure 7.** Base shear force-displacement curves of specimens with different CFRP bar percentages

![Figure 8. Base shear force-displacement curves of specimens with different concrete compressive strength](image)

**Figure 8.** Base shear force-displacement curves of specimens with different concrete compressive strength
It is apparent from this figure that by increasing concrete compressive strength, the flexural capacity of columns enhanced but on the other hand the ultimate displacement of column decreased considerably.

3.4 Equivalent CFRP Bar Ratio with Steel Reinforcement Ratio in Columns

In this section three concrete columns reinforced with steel rebar were modeled in finite element program. In order to find equivalent CFRP bar ratio which leads to the same column strength, steel reinforcement was then replaced by CFRP bars with various diameter. Specimen properties are given in the table below.

Table 4. Specimen properties

<table>
<thead>
<tr>
<th>specimen</th>
<th>Section dimension (cmxcm)</th>
<th>Height of column (m)</th>
<th>Longitudinal rebar</th>
<th>Rebar percentage (%)</th>
<th>Compressive strength of concrete (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>fc40-f6</td>
<td>40x40</td>
<td>1</td>
<td>CFRP</td>
<td>0.21</td>
<td>40</td>
</tr>
<tr>
<td>fc40-f8</td>
<td>40x40</td>
<td>1</td>
<td>CFRP</td>
<td>0.38</td>
<td>40</td>
</tr>
<tr>
<td>fc40-f10</td>
<td>40x40</td>
<td>1</td>
<td>CFRP</td>
<td>0.59</td>
<td>40</td>
</tr>
<tr>
<td>fc40-s10</td>
<td>40x40</td>
<td>1</td>
<td>STEEL</td>
<td>0.59</td>
<td>40</td>
</tr>
<tr>
<td>fc40-s12</td>
<td>40x40</td>
<td>1</td>
<td>STEEL</td>
<td>0.85</td>
<td>40</td>
</tr>
<tr>
<td>fc40-s14</td>
<td>40x40</td>
<td>1</td>
<td>STEEL</td>
<td>1.15</td>
<td>40</td>
</tr>
</tbody>
</table>

Force-displacement curves obtained from analysis indicates that replacing CFRP bars instead of steel rebars in columns to achieve the same strength leaded to use CFRP bars with lower diameters or in other words ratio of CFRP reinforcement to the ratio of steel reinforcement in a same strength is significantly less.

![Figure 9. Base shear force-displacement curves of specimens](image)

In the curves above the ultimate displacement of columns strengthened with CFRP bars occurred when CFRP bar strains reached to the rupture strain, but the columns with steel reinforcement didn’t reach to their ultimate displacement (It should be mentioned that ultimate displacement of steel reinforced columns considered at 80% of column strength).

From Figure 10 it can be seen that column with CFRP bars reinforcement ratio of 0.59% reached to 13.71 mm displacement at the strength of 211.28kN and the column with steel reinforcement ratio of 1.15% reached to 8.65 mm displacement at the strength of 210.38kN. Due to less modulus of elasticity of CFRP bars in comparison with steel rebar, the columns reinforced with CFRP bars showed more flexible behavior initially and the maximum base shear occurred at greater displacement, then because of elastic and brittle behavior of CFRP material, CFRP bars reached to their rupture strain and the ultimate displacement of column
occurred but in columns reinforced with steel rebar, after yielding of steel rebar, columns entered to plastic phase and tolerate more displacement.

![Figure 10. Base shear force-displacement curves of columns with CFRP bars reinforcement ratio of 0.59 and steel reinforcement ratio of 1.15%](image)

According to the results obtained from this study we can use lower percentage of FRP bars in column cross section compared to steel rebar percentage to reach the same strength. Using FRP bars to design concrete columns in addition to reducing structural weight, prevent steel corrosion and deterioration of concrete especially in structures near seashore, bridges piers etc. It should be considered that brittle behaviors of columns reinforced with CFRP bars don’t make any problems for structures because in the structures columns expected to behave elastically when other members like beams and braces behave plastically.

### 3.5 Conclusions

In this paper to evaluate the effect of replacing steel rebar with CFRP bars, column specimens reinforced with CFRP bars were modeled in finite element program. The effects of parameters such as ratio of longitudinal CFRP reinforcement and concrete strength on base shear force and ultimate displacement of columns were then investigated. In continuation the equivalent CFRP bar ratio needed to be replaced instead of steel rebar to reach the same column strength was found.

The results obtained from studies can be summarized as follows:

- In column specimens with constant concrete strength, increasing CFRP bars ratio enhanced column flexural strength and also increased the ultimate displacement of column.
- In column specimens with constant CFRP bar ratio increasing concrete compressive strength, enhanced flexural capacity of columns but on the other hand the ultimate displacement of column decreased.
- For designing columns, steel rebar can be replaced by lower ratio of CFRP bars in section to reach the same strength. However the columns strengthened with CFRP rebar behaved more brittle and tolerated less displacement (because of reaching to CFRP rupture strain) than columns reinforced with steel rebar, it may not cause any problems for structures. Because based on capacity design method, in the structures columns expected to stay in their elastic phases until other members such as beams and braces go to their plastic phases.
- Using FRP bars to design concrete columns in addition to reducing structural weight,
prevent steel corrosion and deterioration of concrete especially in structures near seashore, bridges piers etc.; however it should be note that the columns with CFRP reinforcement can tolerate less ultimate displacement.

- Designing columns with lower ratio of rebar (FRP bars instead of steel rebar) prevent confusion of column’s cross sections. Moreover to reach higher strength, FRP ratio can be increased and cross section dimensions of columns can be decreased.

3.6 References


