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Confinement effect of FRP and transverse steel on retrofitting square concrete columns

Le V. Doan
University of Wollongong

Xu Lei
University of Wollongong, xl158@uowmail.edu.au

Muhammad N. S Hadi
University of Wollongong, mhadi@uow.edu.au

Thong m. Pham
University of Wollongong

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Abstract
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Keywords
retrofitting, confinement, square, concrete, effect, frp, transverse, steel, columns

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CONFINEMENT EFFECT OF FRP AND TRANSVERSE STEEL ON RETROFITTING SQUARE CONCRETE COLUMNS

Le V. Doan, Xu Lei, Thong M. Pham and Muhammad N.S. Hadi *
School of Civil, Mining & Environmental Engineering, University of Wollongong, Wollongong, NSW, Australia
*Email: mhadi@uow.edu.au.

ABSTRACT

This study presents an experimental investigation into strain distribution of Fibre-Reinforced Polymer (FRP) in FRP-confined concrete columns with internal steel reinforcement under concentric and eccentric loading conditions. A total of nine reinforced concrete columns were cast and tested. Three of them were square in cross-section while the others were originally square but were shape-modified into circular columns with four pieces of segmental circular concrete covers and confined with three layers of CFRP. The nominal compressive strength of the segmental concrete covers was 40 MPa and 80 MPa. All columns were tested under concentric load, 25 mm or 50 mm eccentric load. Strain distribution was obtained by a number of strain gauges located symmetrically around the circumference of the columns. The CFRP strain distribution in the hoop direction and the hoop rupture strain of the shape-modified reinforced concrete columns under different load eccentricity was examined. Moreover, the load-carrying capacity and ductility were compared with columns with different volumetric ratio of transverse steel reinforcement from a previous study to discover the effect of transverse steel confinement on the ductility of FRP-confined columns under both concentric and eccentric load. Results showed that the hoop strain distribution for eccentrically loaded columns was not uniform with the maximum strain that occurred at the extreme compression fibre while the minimum strain occurred at the extreme tension fibre of the columns. The variation of the CFRP hoop strain increased when the eccentricity increased. In addition, columns with different volumetric ratio of transverse steel reinforcement had similar normalised stress and ductility, suggesting that transverse steel reinforcement is insignificant effect on the load-carrying capacity and ductility of FRP-confined columns.

KEYWORDS

Shape modification, eccentric loading, strain distribution, confinement.

INTRODUCTION

Fibre-Reinforced Polymer (FRP) provides passive confining pressure to restrain the lateral expansion of concrete columns under axial loading. Previous studies indicated that the compressive strength and the ultimate strain of FRP-confined concrete are closely related to the confining pressure provided by the FRP jacket when it ruptures (Lam and Teng 2003; Pessiki et al. 2001). However, the majority of these theoretical models focused on columns under concentric loading. It is apparent that columns under eccentric loading exhibit non-uniform expansion in the hoop direction and therefore the strain distribution in the FRP jacket would be non-uniform. To better understand the strain distribution in the FRP jacket of eccentrically loaded concrete columns, an experimental program is presented in this study evaluating the strain distribution in the FRP jackets for the columns under both concentric and eccentric loading conditions.

A theoretical study by Pellegrino and Modena (2010) revealed that internal transverse steel reinforcement influences the behaviour of FRP-confined columns by contributing transverse confining pressure. Theoretical models which neglect the confining pressure may underestimate the stress-strain behaviour of the FRP-confined columns with internal reinforcement. The effect of internal transverse steel reinforcement is validated in the latter part of this study by comparing test results of FRP-confined columns with different volumetric ratio of internal transverse steel reinforcement.
EXPERIMENTAL PROGRAM

Tests on nine columns were conducted in the High Bay of the Civil Engineering Laboratory of the University of Wollongong. Details of the experimental program are presented in this section.

Design of Specimens

The dimension of each square column was 150 mm in sides and 800 in height. All the columns were made of normal strength concrete (NSC) and the steel reinforcement of columns were designed in accordance with AS 3600 (2009) with a small amount of internal steel reinforcement. Longitudinal steel reinforcement consisted of four 12 mm (N12) deformed bars with a nominal tensile strength of 500 MPa tied inside by transverse steel reinforcement. The diameter of the transverse steel reinforcement was 6 mm (R6) with a nominal tensile strength of 250 MPa, which was placed at 60 mm spacing. The clearance between the steel reinforcement and the mould was maintained at 20 mm on each side, at the top and the bottom.

Six of the test specimens were shape-modified by bonding four segmental circular plain concrete covers to each side. Segmental circular plain concrete covers were cast with NSC and high strength concrete (HSC), with a nominal compressive strength of 40 MPa and 80 MPa, respectively. The modified columns were then confined with three layers of CFRP. Figure 1 shows the design details of the specimens.

![Design details of the specimens](image)

In total, nine RC columns were tested and subdivided equally into three groups. From each group, the columns were tested under concentric loading or eccentric loadings with 25 mm and 50 mm eccentricity. Details of the specimens are presented in Table 1. The labelling used for the specimens is composed of a combination of letters and numbers. The letters R and C denote the reference columns and the shaped-modified columns, respectively. The numbers 40 and 80 express the nominal compressive strength of the segmental circular concrete covers which were bonded to the existing square RC columns. The last number 0, 25 and 50 denote the eccentricity of the axial loading. For example, Specimen C80-50 is the shape-modified column with concrete covers of 80 MPa and tested under an eccentric loading of 50 mm.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Concrete strength at test time (MPa)</th>
<th>Steel reinforcement</th>
<th>Number of CFRP layers</th>
<th>Eccentricity (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-0</td>
<td>44</td>
<td>4N12 and R6@60 mm</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>R-25</td>
<td></td>
<td></td>
<td>-</td>
<td>25</td>
</tr>
<tr>
<td>R-50</td>
<td></td>
<td></td>
<td>-</td>
<td>50</td>
</tr>
<tr>
<td>C40-0</td>
<td>58</td>
<td>4N12 and R6@60 mm</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>C40-25</td>
<td></td>
<td></td>
<td>3</td>
<td>25</td>
</tr>
<tr>
<td>C40-50</td>
<td></td>
<td></td>
<td>3</td>
<td>50</td>
</tr>
<tr>
<td>C80-0</td>
<td>59</td>
<td>4N12 and R6@60 mm</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>C80-25</td>
<td></td>
<td></td>
<td>3</td>
<td>25</td>
</tr>
<tr>
<td>C80-50</td>
<td></td>
<td></td>
<td>3</td>
<td>50</td>
</tr>
</tbody>
</table>
Construction of shaped modified specimens

Two wooden formworks for casting existing square columns and segmental circular concrete covers in this experimental program were used as illustrated by Hadi et al. (2013). The wooden panels for casting the existing columns had internal cross-sections of 150 by 150 mm and 800 mm in height. The second formworks for casting the segmental circular concrete covers had internal cross-sections of 170 by 51 mm and 800 mm in height. Special forms were also used to fit inside the second formworks to prepare the segmental circular covers.

The segmental circular concrete covers were taken out of the formworks after 28 days. The contact surfaces between the segmental covers and the existing columns were ground using a wire brush and an electric grinder in order to achieve a smooth surface. Four segmental circular concrete covers were then bonded to the existing square columns with an admixture, which was made from epoxy resin, slow hardener, and silica microsphere with a ratio of 5:1:10, as recommended by the manufacturer. These modified columns were then confined with three layers of CFRP. A wet lay-up method was applied to bond the CFRP to the columns with adhesive. The adhesive was prepared by mixing an epoxy resin and a slow hardener with a ratio of 5:1.

Preliminary testing

The average compressive strength of concrete at the testing day is shown in Table 1. The tests to measure the tensile strength of N12 deformed bars and R6 plain bars, 542 MPa and 499 MPa, respectively, was conducted in accordance with AS 1391 (2007). The CFRP was tested according to ASTM D3039 (2010) to determine its tensile strength. The test revealed that the tensile strength of the three layered CFRP was 2105 N/mm, corresponding maximum strain of 1.74 %.

Specimen Testing

All the columns were tested using the 5000 kN Denison testing machine to failure. In order to transfer the loading from the machine to the specimens uniformly, each column was levelled by high strength plaster at both ends. The eccentric loading was applied on the columns using the loading heads and the knife edges, as described by Hadi and Widiarsa (2012). The loading heads had two grooves, which were located at 25 mm and 50 mm from their centrelines. Strain gauges (SG) were attached onto the surface of the middle CFRP ring to investigate the actual strain of CFRP in the hoop direction. Four strain gauges were symmetrically bonded in all concentrically loaded columns while each eccentrically loaded column had ten strain gauges, as shown in Figure 2. More strain gauges were installed in the compression region due to the largest confining pressure of the CFRP in this region. The axial load was measured by the load cell of the 5000 kN Denison Compression machine at the University of Wollongong. Two LVDTs were attached to the lower plate of the loading machine to measure the axial deflection of the columns. For columns that were subjected to eccentric loading (25 mm and 50 mm), a laser triangulation was set up at the mid-height of the columns to record their lateral deflection. All specimens were tested under displacement control with a loading rate of 0.3 to 0.5 mm/min.

RESULTS AND DISCUSSIONS

Distribution of CFRP hoop strain under different loading conditions

The CFRP strain in hoop direction (out of the overlap zone) of the concentrically loaded columns was almost uniform. However, the CFRP hoop strain became the largest at the extreme fibre in the compression region of the columns under the eccentric loading.

Concentrically loaded columns

The CFRP of concentrically loaded columns ruptured at the ultimate load. The CFRP hoop strain at rupture was calculated from the average values from the strain gauges outside the overlap zone. The average hoop strains in the CFRP at failure were approximately 1.29% and 1.05% for Specimens C40-0, C80-0, respectively. In addition, the smallest strain was always found within the overlap zone, which was about 75% of the average strain in CFRP at rupture. This is because the thickness of CFRP within the overlap zone was thicker than
outside the overlap zone. The strain in the jacket is inversely proportional to the thickness of the jacket for the same confinement pressure.

Table 2. Results of CFRP strain at rupture for concentrically loaded columns

<table>
<thead>
<tr>
<th>Specimen</th>
<th>C40-0</th>
<th>C80-0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate Load (kN)</td>
<td>3343</td>
<td>3462</td>
</tr>
<tr>
<td>CFRP strain at rupture (%)</td>
<td>1.29</td>
<td>1.05</td>
</tr>
<tr>
<td>CFRP strain in overlapping zone at failure (%)</td>
<td>1.01</td>
<td>0.81</td>
</tr>
<tr>
<td>Strain efficiency factor</td>
<td>0.74</td>
<td>0.60</td>
</tr>
</tbody>
</table>

As stated above, the average ultimate strain from flat coupon tests was 1.74%. The CFRP strain efficiency factor of these specimens, defined as the ratio of the actual hoop rupture strain to the ultimate strain of CFRP from flat coupon tests, are given in Table 2.

**Eccentrically loaded columns**

The CFRP rupture of eccentrically loaded columns did not simultaneously occur when these columns achieved the ultimate load, as shown in Figure 3. Therefore, the CFRP strain distributions of these specimens were obtained at the ultimate load and at CFRP rupture. The CFRP strain was the highest at the extreme compression fibre, whereas the smallest strain arose at the extreme tension fibre of the columns. The CFRP strain decreased gradually from the extreme compression fibre to the extreme tension fibre, as shown in Figure 4. Figure 4 also shows the strain on the overlap zone compared with the hoop strain distribution over the columns’ circumference. The CFRP strains within the overlap zone were always lower than those outside the overlap zone. The strains at the extreme compression fibre were 5.3 and 3.3 times higher than those at the extreme tension fibre when Specimen C80-25 achieved the ultimate load and the CFRP ruptured, respectively. Similarly, these ratios were 10.8 and 9.3 respectively for Specimens C80-50. The results demonstrated that the disproportion between the CFRP strain at the extreme compression fibre and at the extreme tension fibre increased with increasing load eccentricity.

Table 3. CFRP hoop strain of the columns at extreme compression fibre at rupture

<table>
<thead>
<tr>
<th>Eccentricity</th>
<th>CFRP hoop strain of the columns</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C40 group</td>
</tr>
<tr>
<td>Concentric loading</td>
<td>1.29%</td>
</tr>
<tr>
<td>25 mm Eccentric loading</td>
<td>1.13%</td>
</tr>
<tr>
<td>50 mm Eccentric loading</td>
<td>1.22%</td>
</tr>
</tbody>
</table>

The strain efficiency factor of CFRP under eccentric load is defined as the ratio of CFRP strain at the extreme compression fibre at the ultimate load to the rupture strain of CFRP from flat coupon tests. The higher the load
eccentricity, the lower strain efficiency factor was obtained. For example, the strain efficiency factors were 0.67, 0.4 and 0.26 for the columns under concentric loading, 25 mm eccentric loading and 50 mm eccentric loading. These values were calculated from the average values of the FRP strain efficiency factor from Group C40 and C80. Table 3 shows the result of the CFRP rupture strains in the hoop direction at the extreme compression fibre, which was quite similar to the value of CFRP rupture strain under concentric loading. It is believed that CFRP ruptured when the maximum CFRP hoop strain achieved about 0.68% of the ultimate strain of CFRP from flat coupon tests.

**Influence of internal transverse steel reinforcement**

To further investigate the influence of transverse steel reinforcement on FRP-confined columns, four specimens were taken from the study by Hadi et al. (2013) and compared with the relevant specimens in this study. The specimens had the same geometry and FRP-confinement except that the compressive strength of concrete in Hadi et al. (2013) was 27 MPa. The same amount of longitudinal reinforcement was maintained but the ties used by Hadi et al. (2013) had 120 mm spacing compared with 60 mm spacing in current study. Both specimens under concentric and eccentric loading with 25 mm eccentricity are compared. Details of the specimens are given in Table 4.

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Tie spacing (mm)</th>
<th>Yield Load (kN)</th>
<th>Corresponding Deflection (mm)</th>
<th>Ultimate Load (kN)</th>
<th>Corresponding Deflection (mm)</th>
<th>Ductilityb</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-0</td>
<td>60</td>
<td>894</td>
<td>4.28</td>
<td>919</td>
<td>4.93</td>
<td>1.39</td>
</tr>
<tr>
<td>N-0a</td>
<td>120</td>
<td>707</td>
<td>1.31</td>
<td>717</td>
<td>1.46</td>
<td>1.41</td>
</tr>
<tr>
<td>C40-0</td>
<td>60</td>
<td>2140</td>
<td>2.82</td>
<td>3343</td>
<td>13.72</td>
<td>4.96</td>
</tr>
<tr>
<td>CF-0a</td>
<td>120</td>
<td>1478</td>
<td>2.01</td>
<td>2907</td>
<td>13.35</td>
<td>6.98</td>
</tr>
<tr>
<td>R-25</td>
<td>60</td>
<td>615</td>
<td>2.84</td>
<td>633</td>
<td>3.13</td>
<td>1.15</td>
</tr>
<tr>
<td>N-25a</td>
<td>120</td>
<td>414</td>
<td>0.96</td>
<td>427</td>
<td>1.08</td>
<td>1.33</td>
</tr>
<tr>
<td>C40-25</td>
<td>60</td>
<td>1421</td>
<td>3.43</td>
<td>1519</td>
<td>6.03</td>
<td>3.97</td>
</tr>
<tr>
<td>CF-25a</td>
<td>120</td>
<td>1011</td>
<td>1.08</td>
<td>1170</td>
<td>6.12</td>
<td>5.11</td>
</tr>
</tbody>
</table>

Denotes specimens taken from Hadi et al. (2013).

Ductility is calculated as the ratio of the deflection at 85% post-peak load to the deflection at yield load.

The normalised stress-deflection diagrams for specimens under concentric load and 25 mm eccentric load are shown in Figure 5. The normalised stress was calculated as the ratio of cross-sectional stress to the compressive strength of unconfined concrete. The cross-sectional stress was calculated as the axial force divided by the gross cross-sectional area. It is evident that the specimens with different transverse steel reinforcement behaved in a similar manner. Specimens with smaller tie spacing achieved similar normalised yield and ultimate stress as shown in Table 4. This is probably due to the fact that confining pressure provided by transverse steel reinforcement is much smaller than that by FRP (only between 1% to 7% of the confining pressure provided by FRP). In addition, improvement in ductility was not witnessed for columns with smaller tie spacing. This is mainly due to the instrumentation-related errors. Further experimental investigations on columns with various tie spacing are required to evaluate the effect of tie spacing on FRP-confined columns.

![Figure 5. Specimens with different transverse steel reinforcement](image-url)
CONCLUSIONS

Based on test observation in the experimental program, the following conclusions can be drawn:

The CFRP strain efficiency factors, which were calculated at the ultimate loads, were 0.67, 0.4 and 0.26 for these specimens under concentric loading, 25 mm eccentric loading and 50 mm eccentric loading, respectively. The CFRP rupture strains at the compression tension fibre under eccentric loading were quite similar to the value of CFRP rupture strain under concentric loading. The disproportion between the CFRP strain at the extreme compression fibre and at the extreme tension fibre increased with increasing load eccentricity.

The difference in transverse reinforcement in FRP confined reinforced concrete columns is negligible in terms of normalised compressive stress, which indicates that the contribution of steel ties is marginal compared to the contribution of FRP. In addition, the ductility of the columns is not affected by the amount of transverse steel reinforcement based on this study but further investigation is encouraged.

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