Experimental study on the stress-strain relation of PVC-CFRP confined reinforced concrete column subjected to eccentric compression

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(Received June 2, 2019, Revised July 23, 2020, Accepted August 5, 2020)

Abstract. An experimental study on the stress-strain relation of PVC-CFRP confined reinforced concrete columns subjected to eccentric compression was carried out. Two parameters, such as the CFRP strips spacing and eccentricity of axial load, were considered. The experimental results showed that all specimens failed by compressive yield of longitudinal steel bar and rupture of CFRP strips. The bearing capacity of specimen decreases as the eccentricity or the CFRP strips spacing increases. The stress-strain relation of specimens undergoes two stages: parabolic and linear stages. In the parabolic stage, the slope of stress-strain curve decreases gradually as the eccentricity of axial loading increases while the CFRP strips spacing has little effect on the slope of stress-strain curve. For the linear stage, the slope of stress-strain curve decreases as the eccentricity of axial load or the CFRP strips spacing increases. A model for predicting the stress-strain relation of columns under eccentric compression is proposed and it agrees well with various test data.

Keywords: PVC-CFRP confined concrete; eccentric compression; failure mode; stress-strain relation

1. Introduction

Polyvinyl chloride-fiber reinforced polymer (PVC-FRP) tube confined concrete, consisted of PVC-FRP tube, steel bars, and core concrete, is a new composite structure, which has some advantages, such as light weight, high strength, convenient construction and corrosion resistance (Yu 2007, Yu et al. 2018). For the new structure, PVC-FRP tube is made by winding FRP strips on a PVC tube according to the design spacing. Longitudinal reinforcing bars and stirrups are binded and placed in the PVC-FRP tube, which is finally filled with concrete. As a result, the PVC tube can be used as a formwork for construction due to its rigidity. Additionally, the PVC-FRP tube can effectively confine the core concrete to increase the bearing capacity and ductility.

As PVC-FRP confined concrete has excellent mechanical and durability performance, PVC-FRP confined concrete structure has gained increasing research interest, and some achievements have been made. Kurt firstly investigated the behavior of concrete filled PVC tube, a new composite structure (Kurt 1978). After that, some studies have been performed on this type of composite structure (Wang and Yang 2016, Gupta 2013, Naftary et al. 2014). Saafi investigated the axial bearing mechanism of grooved PVC-FRP confined concrete column and analyzed the influence of FRP type, CFRP strips spacing, and reinforcement ratio. The results showed that the bearing capacity and deformation increased as the confinement of PVC-FRP tube increased. Models for estimating the bearing capacity and the stress-strain relation were proposed (Saafi 2001). Jiang studied the PVC-BFRP confined concrete column and analyzed the effect of BFRP strips layer on the failure mode, bearing capacity and stress-strain relation. The results indicated that the bearing capacity and ductility increased significantly as the BFRP strips layer increased. The stress-strain relation of specimens underwent two stages: parabolic and linear stages (Jiang et al. 2012, Jiang et al. 2014). From the results of the experiment, a formula was put forward to calculate the ultimate compressive strength of such composite columns. Experiments of PVC-CFRP confined concrete short columns subjected to axial compression were performed by Yang, and the influence of FRP type on the mechanical properties was investigated (Yang 2014). The results showed that FRP can significantly improve the ultimate bearing capacity and ductility of the columns. In addition, the bearing capacity of PVC-CFRP confined concrete column was obviously higher than that of PVC-GFRP confined concrete column (Yang 2014). Fakharifar investigated a new composite confining system, which was composed of FRP strips and PVC tube with compressible foam inside. The results indicated that the compressible foam can improve the compressive strength and ductility (Fakharifar and Chen 2016). Yu experimentally studied the mechanical properties of PVC-CFRP confined concrete column under axial compression. The effects of CFRP strip spacing, reinforcement ratio, and slenderness ratio on the failure mode, bearing capacity, stress-strain relation were investigated. The models of the bearing capacity, stress-strain relation, and axial ultimate strain for the columns were proposed (Yu and Niu 2010, Yu and Niu 2013, Yu and Xu 2015, Yu et al. 2015).

Jiang investigated the effect of the type and layer of FRP, and axial compression ratio on the seismic behavior of
PVC-FRP confined reinforced concrete columns. The results showed that the hysteretic curve of the columns was full due to the confinement of PVC-FRP tube. In addition, the hysteretic performance of the columns confined by CFRP was better than that of the columns confined by BFRP (Jiang et al. 2014). Yu analyzed the effect of CFRP strips spacing, axial compression ratio and shear span ratio on the seismic performance of PVC-CFRP confined reinforced concrete columns. The calculating methods of the characteristic parameters of skeleton curves and the hysteresis rules were proposed, and the storing force model of the columns was established (Yu et al. 2015, 2016).

Ranney studied the durability of PVC tube and GFRP wrap against chloride ion and freeze-thaw. The results indicated that the performance of the PVC tube was similar with that of GFRP wrap, and PVC tube showed better chemical resistance than GFRP wrap (Ranney and Parker 1995). PVC tube had no degradation in hot and cold cycles, and it satisfied the requirements of the NSF standard (Case study of PVC geomembrane durability 1998). Toutanji and Yu also found PVC-CFRP confined concrete had good durability (Toutanji and Saafi 2001, Yu and Niu 2014, 2016).

As described above, there are numerous researches on the mechanical behavior of PVC-FRP confined concrete column. However, these studies are mainly focusing on the axial compression, seismic performance and durability. The mechanical properties of PVC-CFRP confined reinforced concrete columns under eccentric compression have not been studied. Hence, this study presents an experiment study on the stress-strain relation of PVC-CFRP confined reinforced concrete columns under eccentric compression.

### 2. Experimental program

Twenty-four PVC-CFRP confined reinforced concrete columns subjected to eccentric compression were conducted. The diameter and length of all specimens were 200 mm, 500 mm, respectively. Different CFRP strips spacing (i.e., 20 mm, 30 mm, 40 mm, 50 mm, and 60 mm) and different eccentricity (i.e., 20 mm, 40 mm) were considered, as shown in Table 1. Each specimen consisted of eight steel bars with 10 mm diameter, and the reinforcement ratio was 1.8%. The length-diameter ratio of PVC-CFRP tube was approximately 2.5. The 20-mm-width of CFRP strips with three layers was designed, and the thickness of single layer was 0.11 mm.

From the test results of materials, the ultimate tensile strength of CFRP strip was 3612 MPa, and the tensile strength of PVC tube was 62 MPa, as listed in Table 2. The compressive strength of concrete was 42.6 MPa. The tensile yield strength of longitudinal steel bar was 313 MPa, as shown in Table 2.

### Table 1 Specimens of PVC-CFRP confined reinforced concrete column

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Hoop spacing (mm)</th>
<th>Eccentricity, e, (mm)</th>
<th>Bearing capacity, $F_u$ (kN)</th>
<th>Increase of bearing capacity (%)</th>
<th>Mid-height deflection, $d_h$ (mm)</th>
<th>Bending moment, $M_u$ (kN·m)</th>
<th>Increase of bending moment (%)</th>
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<tbody>
<tr>
<td>E20-PVC-1</td>
<td>-</td>
<td>20</td>
<td>1177.30</td>
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<td>20</td>
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<td>4.52</td>
<td>44.95</td>
<td>51.23</td>
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<td>4.25</td>
<td>41.85</td>
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<tr>
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<td>20</td>
<td>1626.00</td>
<td>42.88</td>
<td>5.21</td>
<td>40.99</td>
<td>37.93</td>
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<td>40</td>
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<td>19.93</td>
<td>6.04</td>
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<td>6.00</td>
<td>50.27</td>
<td>16.00</td>
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</tbody>
</table>

Note: All the tested columns have been given labels in the form of E-CsXX-b, in which E denotes the specimen that is subjected to eccentric compression, Cs denotes the specimen that is winded with CFRP strips, XX denotes the hoop spacing of CFRP strip, and b is the number for the specimens with the same configuration.
Table 2 Material properties of confined reinforced concrete columns

<table>
<thead>
<tr>
<th>Material</th>
<th>Elastic modulus (MPa)</th>
<th>Yield strength (MPa)</th>
<th>Ultimate strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFRP (Tension)</td>
<td>224000</td>
<td>3612</td>
<td>4571</td>
</tr>
<tr>
<td>PVC (Tension)</td>
<td>3160</td>
<td>62</td>
<td>-</td>
</tr>
<tr>
<td>Concrete (Compression)</td>
<td>-</td>
<td>-</td>
<td>42.6</td>
</tr>
<tr>
<td>Longitudinal steel bar (Tension)</td>
<td>211000</td>
<td>313</td>
<td>344</td>
</tr>
</tbody>
</table>

Fig. 1 Arrangement of measuring instruments

For each specimen, six displacement meters were arranged at the both sides of the center and both ends to measure the displacement, as shown in Fig. 1. Eight unidirectional strain gauges were placed at the mid-height of specimen and PVC tube to get the strains of CFRP strips and PVC tube. In addition, one strain gauge was affixed on each longitudinal steel bar to investigate its strain variation.

According to the related experimental standard (Standard for test method of concrete structures GB/T 50152, 2012), both ends of the specimen were loaded with an edge hinge to simulate the boundary conditions of the column. Initial eccentricity was established from the distance between the edge and the sectional center of the specimen. All specimens were subjected to monotonic static loading, and each step of loading was 10% of the ultimate bearing capacity. When the loading reached the ultimate bearing capacity of specimen, a slow continuous loading was applied until the specimen failed.

3. Experimental results analysis

3.1 Failure mode

For the PVC-CFRP confined reinforced concrete columns with large eccentricity, it failed by compressive yield of longitudinal steel bar and rupture of CFRP strips, as shown in Fig. 2. On the side of compression, the longitudinal steel bar yielded, and the concrete and PVC tube were crushed. On the tensile side, the longitudinal steel bar also yielded, and the PVC tube was pulled off. In addition, the CFRP strips were broken. After removing PVC tube, several main cracks were found in the tensile area of the concrete.

Fig. 2 Failure mode of specimens under large eccentric compression

Fig. 3 Failure mode of specimens under small eccentric compression
For the PVC-CFRP confined reinforced concrete columns with small eccentricity, the failure mode was similar with that of the specimen subjected to large eccentricity, as shown in Fig. 3. The longitudinal steel bar on the compressive side yielded, and the concrete and PVC tube were crushed. In addition, CFRP strips fractured. However, the tensile strain of longitudinal steel bar and PVC tube on the tensile side was small. Due to the confinement of the CFRP strips, the specimen showed better deformability than that of the specimen without CFRP.

3.2 Bearing capacity

The bearing capacity of PVC-CFRP confined reinforced concrete columns under eccentric load is shown in Table 1. Obviously, the bearing capacity of the PVC-CFRP columns with small eccentricity was 15%-61% higher than that of PVC columns. In contrast, the bearing capacity of the PVC-CFRP columns with large eccentricity was 7%-47% higher than that of PVC columns.

Clearly, the bearing capacity of columns decreased as the eccentricity or the CFRP strips spacing increased, as shown in Table 1. This may attribute by the confining effect of PVC-CFRP tube to the core concrete. For specimen with small eccentricity, compression is the main force. As the Poisson's ratio of concrete is larger than that of the PVC-CFRP tube, the confining effect of PVC-CFRP tube to the core concrete is more effective. In contrast, the bending moment of the columns was relatively large when the eccentricity was large. As a result, the tensile zone increased and the compressive zone of cross section decreased, and the confining effect of PVC-CFRP tube to the core concrete became less effective.

3.3 Bending moment

The bending moment of specimens can be estimated from Eq. (1).

\[ M_u = F_u (e + d_e) \]  \hspace{1cm} (1)

Where \( M_u \) is the bending moment; \( F_u \) is the bearing capacity; \( e \) is the eccentricity; and \( d_e \) is the mid-height deflection of column at the bearing capacity.

Clearly, the bending moment of the PVC-CFRP columns with small eccentricity was 12%-51% higher than that of PVC columns. In contrast, the bending moment of the PVC-CFRP columns with large eccentricity was 5%-44% higher than that of PVC columns.

The bending moment of column increased as the eccentricity increased. For example, the bending moment of specimen E40-Cs20-1 was 1.40 times of that of specimen E20-Cs20-1. The bending moment decreased as the CFRP strips spacing increased. Take specimens E40-Cs20-1 and E40-Cs60-1 as an example, the bending moment of specimen E40-Cs60-1 was 27% lower than that of specimen E40-Cs20-1.

4. Stress-strain relation

From the experimental results, various stress-strain curves of PVC-CFRP confined reinforced concrete columns under eccentric compression were obtained. Generally, the curve can be divided into two stages: parabolic and linear stage. Initially, the stress-strain relation was parabolic, which was similar to that of plain concrete columns. This indicates that the PVC tube has little confining effect on the core concrete. When the loading reached the compressive strength of the plain concrete, the internal cracks appeared on the concrete, and the volume of the concrete expanded. Then the PVC-CFRP tube started to limit the expansion of the concrete. Correspondingly, the stress-strain curve had a significant turning point, and it entered the linear stage, as shown in Fig. 4. After that, the confining effect of PVC-CFRP tube to the core concrete increased gradually as the loading increased. Finally, the PVC tube and CFRP strip failed when the column reached the ultimate bearing capacity. Obviously, the bearing capacity and ductility of the core concrete improves a lot due to the confining effect of PVC-CFRP tube to the core concrete.

The effect of CFRP strips spacing on the stress-strain relation of PVC-CFRP confined reinforced concrete columns is shown in Fig. 4. For the column with small
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Eccentricity, the effect of CFRP strips spacing on the stress-strain relation was small when the strain was less than 0.0016. After the stress-strain curve of the specimen entered the linear stage, the slope of the curves decreased as the CFRP strips spacing increased. This is due to the reduction of the confining effect of PVC-CFRP tube to the core concrete.

For the column with large eccentricity, the influence of CFRP strips spacing on the stress-strain relation was similar to that of the column with small eccentricity. However, the slope of stress-strain curve in the linear phase was smaller, and the degree of stress reduction was greater.

The effect of the eccentricity on the stress-strain relation of PVC-CFRP confined reinforced concrete columns is shown in Fig. 5. Yu’s test of PVC-CFRP confined reinforced concrete columns with same configuration under axial compression was also collected (Yu 2007). Obviously, the effect of the eccentricity on the stress-strain relation was significant. The slope of the stress-strain curve and ultimate stress decreased as the eccentricity increased.

5. A model for predicting the stress-strain curve of specimens

Saafi proposed a stress-strain model of grooved PVC-CFRP confined reinforced concrete columns subject to axial compression (Saafi 2001). From the results of experiment, the confining mechanism of PVC-CFRP confined reinforced concrete columns is different from CFRP
confined concrete columns. Thus, the existing stress-strain model of CFRP confined concrete column is not suitable for PVC-CFRP confined concrete column (Pan et al. 2017, Jiang and Teng 2007, Ozbakkaloglu et al. 2013, Wu and Jiang 2013, Harajli 2006).

So far, only Yu proposed a stress-strain model for predicting the behavior of PVC-CFRP confined reinforced concrete columns subject to axial compression (Yu 2007). However, Yu’s model is not suitable for predicting the characteristics of PVC-CFRP confined reinforced concrete columns subject to eccentric compression. As a result, a new model is developed for estimating the stress-strain relation of PVC-CFRP confined reinforced concrete columns subjected to eccentric compression on the basis of Yu’s model (Yu 2007).

\[
\sigma_c = 0.58E_c\varepsilon_c - \frac{(E_c - E_c \varepsilon_c)^2}{12f_{ro}}\varepsilon_c^2 \quad (0 \leq \varepsilon_c \leq \varepsilon_e) \quad (2)
\]

\[
\sigma_c = f_{ro} + E_2\varepsilon_c \quad (\varepsilon_c > \varepsilon_e) \quad (3)
\]

where

\[
E_c = 4773\sqrt{f_{co}} \quad (4)
\]

\[
E_2 = \frac{f_{co} \varepsilon_c - f_{ro}}{\varepsilon_c} \quad (5)
\]

\[
f_{ro} = f_0 + k_s \frac{N_s}{A_c} \quad (6)
\]

\[
\varepsilon_e = \frac{3f_{ro}}{(E_c - E_c)} \quad (7)
\]

\[
f_{oc} = 1.24f_{co}(1 + 1.31\varepsilon_{cc}) \quad (8)
\]

\[
\varepsilon_{cc} = 0.0111 + 0.0077\varepsilon_{cc} \quad (9)
\]

\[
f_0 = 24.734(\varepsilon_{cc})^{-0.0892} \quad (10)
\]

\[
\varepsilon_{cc} = 1.16\varepsilon_{cc} \quad (11)
\]

\[
N_s = f_y A_s \quad (12)
\]

\[
\varepsilon_{cc} = \frac{A_f f_t}{A_c f_{co}} k_y \quad (13)
\]

\[
k_y = \frac{s_1}{s'} \quad (14)
\]

where \(f_{oc}\) is the ultimate compressive strength of unconfined concrete; \(f_t\) is the ultimate tensile strength of CFRP strip; \(f_{ro}\) is tensile strength of longitudinal steel bar; \(k_s\) is the coefficient for the improvement of the ultimate axial strain, and \(k_s = 1.16\); \(\xi_{ee}\) is the confining effect coefficient of PVC-CFRP tube to the core concrete for specimen under axial compression; \(e\) is the eccentricity; \(r\) is the radius of the specimen; \(A_c, A_s, A_s\) are the sectional area of CFRP strip, concrete, and longitudinal steel bar; and \(s, s'\) are the width and CFRP strips spacing.

To consider the effect of the eccentricity on the stress-strain relation of PVC-CFRP confined reinforced concrete columns subjected to eccentric compression, a parameter, \(k\), named the reduction coefficient for considering the influences of eccentric compression is suggested, as shown in Eq. (15).

\[
\xi_{ee} = k\xi_{ee} \quad (15)
\]

From the results of test in this study, the reduction coefficient, \(k\), correlates well with the ratio of the eccentricity to the radius of specimen, as shown in Eq. (16) and Fig. 6.

\[
k = -1.868\left(\frac{e}{r}\right)^2 + 0.011\frac{e}{r} + 1 \quad (16)
\]

As a result, the stress-strain relation of PVC-CFRP confined reinforced concrete columns subject to eccentric compression can be estimated by modifying the parameter \(\xi_{ee}\) in Yu’s model through a new parameter \(\xi_{ee}\), as shown in Eq. (15).

To evaluate the accuracy of this proposed model, the stress-strain curves established from experiment in this study are utilized, as shown in Figs. 7 and 8. Clearly, the stress-strain curves exhibit two stages (i.e., parabolic and linear stage) and Eqs. (2) and (3) can be used to represent these curves. Generally, the proposed model makes good agreement with various stress-strain curves including curves of specimens under small eccentricity and large eccentricity, as shown in Figs. 7 and 8. The average error between the predicted maximum stress and the experimental value is only 7.06%. In the proposed model, the concrete material is assumed as an ideal material. However, the inhomogeneity of concrete material and the deviation of construction are normal in engineering. As a result, the curves predicted by the proposed model are usually above the curves of the experimental results.

6. Conclusions

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Fig. 7 Comparison of proposed model and experimental result (small eccentricity)

Fig. 8 Comparison of proposed model and experimental result (large eccentricity)
columns under eccentric compression was carried out. The following conclusions were made:

(1) All specimens failed by the yield of longitudinal steel bar and the rupture of CFRP strips.

(2) Compared with the PVC columns, the bearing capacity of the PVC-CFRP columns with small eccentricity increased by 15%–61%, while the bearing capacity of the columns with large eccentricity increased by 7%–47%.

(3) The bending moment of specimen increased as the eccentricity increased, and the bending moment decreased as the CFRP strips spacing increased.

(4) The stress-strain curve of PVC-CFRP confined reinforced concrete columns under eccentric loading can be divided into two stages: parabolic and linear parts. A new model of the stress-strain relation for PVC-CFRP tube reinforced concrete columns under eccentric compression was proposed, and it agreed well with various test data.

Acknowledgments

This work was financially supported by National Natural Science Foundation of China (No. 51578001, 51608003, 51878002, and 51008001), Natural Science Foundation of Anhui Province (No. KJ2015ZD10 and KJ2018A0046), Key Research and Development Plan of Anhui Province (No. 1704a0802131), Natural Science Foundation of Anhui Province (No. 1908085ME171), and the Outstanding Young Talent Support Program of Anhui Province (No. gxyqZD2016072). This work was also supported by Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number 107.01-2019.322, The work was also funded by Innovation Project for Returnees from Overseas funded by Department of Human resources and Social security, Anhui Province (No. 2019LCX012), and the Graduate Innovation Research Foundation granted by Anhui University of Technology (No. 2016094 and 2016097).

Declarations

We have provided complete information related to Availability of data and material, Competing interests, Funding, Authors’ contributions, and Acknowledgments.

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**JK**