THE COMPARISON OF BEHAVIORS FOR CIRCULAR AND SQUARE CONCRETE-FILLED STEEL TUBE (CFST) UNDER AXIAL COMPRESSION

Shan Tong Zhong

SUMMARY

The behaviors of concentrically loaded short concrete-filled steel circular columns are better than that of square one. Its load carrying capacity is higher and it has more economical benefit. Hence, it is adopted in buildings widely. But in some developed countries, architects are willing to adopt the square CFST columns from the view of convenient arrangement inside the rooms. In our country, the square CFST columns have begun to use in tall buildings also in recent years.

In this paper, the behaviors, structures and economical benefits of circular and square CFST under axial compression are compared detailed. The results of comparison can be referred for designers.

Keywords: Circular and square CFST, axial compression, behaviors, comparison

INTRODUCTION

As every one knows, the behaviors of circular CFST are better than that of square one. Its load carrying capacity is higher and the steel expanse can be cut down. But the some architects are willing to adopt the square CFST columns from the view of convenient arrangement inside the rooms. Hence, in recent years, the square CFST columns have begun to use in some tall buildings.

In developed countries, save steel is not so importance. But in our country, cost reduction of buildings is most importantly. Hence, the advantages and disadvantages for both of these two kinds of CFST columns should have a clearly understands.

1) Behaviors of circular and square CFST under axial compression

1.1 The constitutive relationships of materials

According to the inference of “Unified Theory” suggested by author (Zhong 1995), the change of behaviors for CFST is along with the change of cross sections, and the change is continuously. And the design formula is unified. From which the stress strain relation curves of circular and square CFST under axial compression should be found. Therefore, the constitutive

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relationships of steel and concrete under complex stress states should be determined firstly. The relation curve of stress intensity \( \sigma_i \) versus strain intensity \( \varepsilon_i \) for steel under complex stress state is shown in Fig. 1.

\[
\sigma_i = \frac{1}{\sqrt{2}} \left[ (\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2) \right]^{1/2} \\
\varepsilon_i = \frac{\sqrt{2}}{3} \left[ (\varepsilon_x - \varepsilon_y)^2 + (\varepsilon_y - \varepsilon_z)^2 + (\varepsilon_z - \varepsilon_x)^2 + 3/2 (\gamma_{xy}^2 + \gamma_{yz}^2 + \gamma_{zx}^2) \right]^{1/2}
\]

(1) (2)

The constitutive relationship of steel can be expressed as follows:

\[
\{d\sigma_{ij}\} = [D]\{d\varepsilon_{ij}\} 
\]

in which \([D]\) is the stiffness matrix of steel, in the elastic range is the elastic stiffness matrix \([D]_e\), in the plastic range is the plastic stiffness matrix \([D]_p\), while in the elastic plastic range is \([D]_ep = [D]_e - [D]_p\).

The plastic-crack theory is used to drive the constitutive relationship of core concrete under complex stress situation. It adopts the following expression (Cheng 2001):

\[
\{d\sigma\} = [D]\{d\varepsilon\} 
\]

(3) (4)

In which, Matrix of rigidity \([D]\) is 6X6 matrix. There are 6 unknown parameters in it. And in these parameters there are 22 coefficients, 19 coefficients of which are taken from reference [5] after a little revised. While 3 of these 22 coefficients are determined by test results. By use of the try and rectification method, Cheng (2001) managed to determine the 3 coefficients from a number of experimental curves of circular compression members. Based on the constitutive relationships of core concrete and steel, and longitudinal and radial displacement compatibility, Chen (2001) obtained the average longitudinal stress-strain curves by calculation. By comparing the calculated curves with the experimental curves and adjusting the 3 coefficients thereafter, a satisfying agreement between the calculated and experimental curves was achieved. This method means “The try-error method”. The right constitutive relationship of concrete under complex stress state was got. Owing to the tangent constitutive matrix is the function of concrete’s stress and strain only, hence, this constitutive relationship of concrete suites various form of members. The detail derivation and analysis please refer to Reference [1].

For verification the right of constitutive relationships of steel and concrete mentioned above, especially for verification the right of parameters adopted in the constitutive relationship of core concrete, we calculated a lot of circular CFST axial compressive stub columns to compare with the test curves. It coincides very well. The test curves are taken from the references of Japan, Russia, England and ours. It is a tremendous achievement in the research work of CFST.

### 1.2 Equivalent Cross-sections
Owing to analysis and to compare the behaviors of CFST with various forms, the equivalent cross-sections should be taken for comparison each other. Equivalent cross-section means that the area of steel $A_s$, area of concrete $A_c$ for various forms are equality each other. Then the steel ratio $\alpha = A_s / A_c$ and the confining factors ($\xi = \alpha f_y / f_{ck}; \xi_0 = \alpha f / f_c$) are equal to each other for circular and square CFST. Here $f_y$ and $f$ is yield stress and design strength of steel respectively, $f_{ck}$ and $f_c$ is standard compressive strength and design compressive strength of concrete respectively.

If $B$ denotes the side length of square form, $t_s$ denotes the thickness of plates, then the diameter $D$ and thickness $t$ of equivalent circular cross-section are:

$$D = 2b / \sqrt{\pi} = 1.1284B \quad (5)$$
$$T = D/2 - (B - 2t_s) / \sqrt{\pi} = 0.5D - 0.5642(B - 2t_s) \quad (6)$$

### 1.3 The behaviors of concentrically loaded short CFST

With the constitutive relationships for steel and concrete, the complete average longitudinal stress-strain curves of concentrically loaded short CFST columns with different cross-section geometries are obtained using FE analyses. 3-D FE models are developed using the incremental Lagrange formula, where both material and geometric nonlinearities are taken into consideration. The detail analysis is referred to the reference [1] please.

Fig.2 shows the $\sigma - \varepsilon$ relationship curves for A3 group ($\xi = 1.06$), A7 group ($\xi = 2.69$) and A10 group ($\xi = 2.9$). Each group consists of four columns, which have circular, octagonal, square and rectangular equivalent cross-sections respectively.

![Fig.2 The $\sigma - \varepsilon$ relationship curves for A3, A7, A10](image)

![Fig. 3 Typical $\sigma - \varepsilon$ curves](image)
From Fig. 2, we can see that the behavior of circular Cross-section is better than that of square one. The behavior of octagonal CFST is situated between circular and square cross-section, but it closes to circular. Behavior of equivalent rectangular is more close to square’s, the $\sigma-\varepsilon$ curves of them always exist descending stages and always expresses brittle damage.

Fig. 3 shows the Typical $\sigma-\varepsilon$ curves of concentrically loaded CFST short columns with different cross-section geometries. When the confining factors change from large, medium to small, the final parts of the curves vary from ascending, horizontal to descending. For composite columns with circular and octagonal cross-sections, descending appears when $\xi$ is smaller than 1.0, while for those with square and rectangular cross-sections, descending occurs when $\xi$ is smaller than 3.

2) The comparison of bearing capacity for circular and square CFST

2.1 Compressive strength

According to the definition of limit state, the damage criterion is determined as follows.

(1) For columns which have plastic failure with strain hardening or plastic stage, the ultimate strength should correspond to point $B$, which is the turning point from elastic plastic stage to strain hardening or to plastic stage.

After numerous analyses, it is well justified that for columns with circular cross-section, the strain corresponding to point $B$ is slightly larger or smaller than 3000$\mu$ε. For the convenience of design, the compressive strength $f_{sc}$ of a CFST circular stub column is determined to be the stress corresponding to the longitudinal strain of 3000$\mu$ε.

(2) For columns which have no plastic stage and show only descending load-displacement curve, the ultimate strength should be take as the highest stress on the curve.

Based on the analyses above, the following formulae are recommended.

The compressive standard strength:

$$f_{sc} = (1.212 + B\zeta + C\xi^2)f_{ck}$$  \hspace{1cm} (7)

The compressive design strength:

$$f_{sc} = (1.212 + B_0\zeta_0 + C_0\xi^2)f_c$$  \hspace{1cm} (8)

In which, B and C are coefficients. They depend on the cross-section geometry, as follows.

For circular cross-section:

$$B_c = 0.1759f_y/235 + 0.794$$
$$C_c = -0.1038f_{ck}/20 + 0.0309$$

For square cross-section:

$$B_s = 0.131f_y/235 + 0.723$$
$$C_s = -0.07f_{ck}/20 + 0.0262$$

The confining factors $\zeta = a f_y/f_{ck}$, $\zeta_0 = a f/f_c$.

For three kinds of steel (Q235, Q345, Q390), six kinds of concrete (C30–C80), steel ratio $a = 0.04–0.20$, the standard strength of square CFST $f_{sc}$ is lower 5%–16% than that of circular one. Moreover, we derived the elastic module ($E$) of circular and square CFST. It shows that the elastic module of square cross-section $E_s$ is lower ~13% than that of circular one. Hence, the equivalent axial rigidity and bending rigidity for square cross-section CFST are lower about 13% than that of circular one.
2.2 The bearing capacity of concentrically loaded CFST columns

Strength: For circular
\[ N_c = A_{sc} f_{sc} \]  
For square
\[ N_s = A_{sc} f_{sc} \]  

Stability: For circular
\[ N_c' = \varphi_c A_{sc} f_{sc} \]  
For square
\[ N_s' = \varphi_s A_{sc} f_{sc} \]  

Then,
\[ K = N_s' / N_c' = (\varphi_s / \varphi_c) (f_{sc}/ f_{sc}) \]  

Value of \( K \) shows in Tab. 1 for steel ratio \( \alpha = 0.1 \).

<table>
<thead>
<tr>
<th>Steel</th>
<th>Q235</th>
<th>Q345</th>
<th>Q390</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>C30</td>
<td>C40</td>
<td>C40</td>
</tr>
<tr>
<td></td>
<td>C50</td>
<td>C60</td>
<td>C60</td>
</tr>
<tr>
<td></td>
<td>C70</td>
<td>C80</td>
<td>C80</td>
</tr>
<tr>
<td>( \alpha = 0.1 )</td>
<td>0.86</td>
<td>0.88</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>0.87</td>
<td>0.88</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>0.88</td>
<td>0.89</td>
<td>0.89</td>
</tr>
</tbody>
</table>

Here, \( \varphi_c \) and \( \varphi_s \) are took from Chinese standards DL/T 5085-1999 and GJB 4142-2000 respectively.

From Tab. 1, we can see that the bearing capacity of concentrically loaded square CFST columns are lower than that of circular one.

2.3 The comparison of bearing capacities for beam-columns

In tall and super tall buildings, the columns are under eccentric compressive load in two directions. The calculate formula is as follows:
\[ N / \varphi N_0 + M_x / \gamma_x W_{scx} + M_y / \gamma_y W_{scy} \leq 1 \]  

In which, \( N, M_x, M_y \) ---axial compressive load, bending moments of x and y directions respectively; 
\( N_0 \) ----bearing capacity of concentrically loaded CFST columns; 
\( W_{scx} \) and \( W_{scy} \) ----section modulus of x and y directions for columns respectively; 
\( \gamma_x \) and \( \gamma_y \)----plastic coefficients of x and y directions for columns respectively.

For circular cross-section, it works under axial compressive load \( N \) with the bending moment \( M = \sqrt{M_x^2 + M_y^2} \). But for square one, it works under axial compression \( N \) with two direction bending moments \( M_x \) and \( M_y \). The calculation is not only complex, but also the research work does not ripen yet. The load bearing capacity of square CFST column is lower than that of circular one owing to the \( \varphi_s N_{os} \) is less than that of circular one \( \varphi_c N_{oc} \).

3. The comparison of structures and manufactures

3.1 The composition of cross-sections

The spiral welding steel tube is always used for circular cross-section if the thickness of plate is \( t \leq 20 \)mm. The quality of weld can be guaranteed perfectly, and it saves labor. When the thickness of plate is greater than 20mm, the longitudinal butt weld is adopted, there is only one weld necessary. For square cross-section, two welds even four welds are necessary to form a box cross-section. Therefore, the weld of circular form is less than that of square one. Hence, the
manufacturing cost of circular member is cheaper.

In addition, the butt weld for circular steel tube bears tensile force only, while the butt weld of square steel tube is under complex stress states.

3.2 The connections of columns with beams

The inner diaphragm is always used for square CFST column as shown in Fig.4a. Fig.4b shows the outside strengthening ring is used for circular column. Although the research works of this connection is more ripe, its anti-seismic behavior is well and it is more safety and reliability, but the steel used is more. If the inner diaphragm is used for circular column, the structure of connection is the same as square column as shown in Fig.4c.

Obviously, the welding of inner diaphragm is more difficulty, and it will impede pouring concrete into the tube.

![Fig.4 The connections of column with beams](image)

4. The behaviors of anti-seismic and fireproofing

4.1 The behaviors of anti-seismic

The research work of anti-seismic behaviors for circular CFST columns is riper than that of square CFST columns.

The slenderness of circular column is controlled instead of limited compression ratio. It caused to save steel. Compression ratio means the ratio of compressive force to nominal compression capacity of the column.

Fig. 5 shows the hysteretic curves of concentrically loaded circular CFST members (axial compressive load \(N=A_{sec}f_{sc}\)) and the compression ratio equals to 1.0) under repeat horizontal load. The hysteretic curves are very full and round. The absorbing energy ability is very well.

The research of anti-seismic behaviors for square CFST columns is lack yet. When it is used as the columns in tall building, the axial compression ratio should be limited as for steel structures.

4.2 The behaviors of fireproofing
We have had completed the research works about fire proofing of circular CFST members, and obtained the calculation formula for determination the thickness of fireproofing coating. The needed thickness of fireproofing coating for circular and square CFST members can be compared as follows.

The circumferential length of circle is \( L_c = \pi D \), for square is \( L_s = 4B \).

According to the equivalent area, \( D = 1.1264B \), hence,

\[
\frac{L_s}{L_c} = \frac{4B}{(1.1264\pi B) = 1.1284}
\]

It means that the coat needed for square members is over 13% more than that for circular one. It is calculated according to the equivalent cross-section. As everyone knows, the area of square cross-section should be enhanced to bear the same loadings of circular cross-section. Hence, the needed fireproofing coat of square members will be still more.

Except fireproofing coat, the fireproofing plates can be used also as shown in Fig. 6. If the thickness of plate is 50mm, the 3h required fireproofing time can be reached.

5. Conclusion

From the comparison of circular and square CFST columns, we can see that the advantages of circular CFST columns are far exceed than that of square one. This is got from the comparisons of the behaviors, structures, manufactures and fire-proofing.

The advantages are as followings:

1) The load carrying capacity under axial compression is about 20% more than that of square cross-section. And under eccentric compression, is 20% more at least. From this the steel and concrete can be saved.

2) The axial and bending rigidities are more 13% about.

3) The behavior of anti-seismic is well. The slenderness of column is controlled instead of to limit the compression ratio.

4) Manufacture is more convenient.

5) The fireproofing coat can be saved 13%.
In a word, the circular CFST column has more advantages. It should be adopted prior in tall and super tall buildings especially in seismic region.

5. Calculating example

Design a CFST column for a tall building,
Known conditions: \( N = 45200kN; M_x = 265kNM; M_y = 38kNM; V = 385kN \); Calculating length \( L_0 = 4.5m \). Used steel Q345 and concrete C50.

The design results are listed in Table 2.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Design results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Circular CFST</td>
</tr>
<tr>
<td></td>
<td>without considered</td>
</tr>
<tr>
<td>Cross-section</td>
<td>( \Phi 1000x22 )</td>
</tr>
<tr>
<td>Rigidity</td>
<td>3148748 kNm²</td>
</tr>
<tr>
<td>Steel used</td>
<td>530.6kg/m</td>
</tr>
<tr>
<td>Save of steel</td>
<td>100%</td>
</tr>
</tbody>
</table>

Reference:

1) Cheng Hongtao, Dissertation of the doctoral degree in engineering(D), Harbin Institute of Technology, Harbin 2001.
2) Zhong Shantong, Concrete Filled Steel Tubular Structures(M), Heilongjiang Science-Technical Publishing House, Harbin, 1995.
3) Design Regulation of Composite Structures(S), DL/T 5085-1999.
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