Comparison for Solid Concrete-filled Circular Steel Tubes Load-carrying Capacities in Frame Structures Basing on Chinese codes

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Abstract: Solid steel tubular concrete members have excellent axial compression capacity. In terms of the calculation method of their axial compression bearing capacity, the current ten domestic standards all provide specific provisions. On the basis of main structure provisions such as diameter-thickness ratio and confinement factor, the formula differences in axial-force compression capability of domestic and international standards are compared and analyzed. First, the difference value of bearing capacities reach up to 62.79% according to current standards when diameter-thickness ratio range from 4 to 30. Second, concrete-filled steel tube members with diameter-thickness ratio greater than 20 and diameter less than 200, the current specifications cannot calculate the axial compressive bearing capacity.

1. Introduction
Major in axial compression and small eccentric compression, concrete-filled steel tubular members are widely used in civil construction, industrial construction, bridge construction and other fields[1-4]. In order to establish a design method for the bearing capacity of concrete-filled steel tube members, many well-known scholars from Harbin Institute of Technology, the Chinese Academy of Building Sciences, Tsinghua University and other units have carried out a large number of theoretical and experimental studies over the years, which have provided an important basis and contribution for the compilation of a series of codes and standards in China. There are 10 copies of solid circular concrete-filled steel tube axial compression members in Chinese current codes and standards[5~14].

In the above standards, there are two main theoretical systems for the design of concrete-filled steel tubes: (1) Unified Theory of Concrete Filled Steel Tubes(hereinafter called “Unified theory”); (2) Experiment-based limit equilibrium theory(hereinafter called “Limit equilibrium theory”). As the comparative study of design methods in the norms and standards, a new method with a simple form and a clear concept is proposed by analyzing the design methods for the bearing capacity of concrete-filled steel tubes in the 7 domestic and foreign codes[15]. Comparing the calculation formulas of concrete-filled steel tube bearing capacity in different regulations in China, it is pointed out that although the formulas of the various regulations have certain differences in form, their essential laws are consistent[16, 17]. Basing on the domestic and foreign design regulations for concrete-filled steel tube columns, a new unified algorithm is proposed on the basis of the Chinese,
American and European standards[18, 19]. Based on the Chinese and British specifications and combined with actual projects, the two specifications on the structure and design requirements of concrete filled steel tube are compared, and it is shows that the requirements of Chinese specifications are more stringent[20]. Introduces the calculation methods of the six codes of China, the United States, Europe and Japan, and compares and analyzes the existing test results, and reveals that the calculation results of the national codes are generally safe[21]. Listing three domestic and five overseas codes and calculated and compared the design formulas for the short column axial compression bearing capacity. The results indicate that the Chinese code is more consistent with the test results[22]. This paper will take the bearing capacity calculation method of the concrete-filled circular steel tube axial compression member as the research object, comparing and analyzing the differences in the 10 norms.

2. Comparative analysis of structural requirements

2.1 regulations of steel and concrete

As shown in Fig.1, regarding the selection of steel and concrete, these codes give a clear selection range of grades and labels, and make clear requirements for its performance: the steel should meet the relevant regulations of the current national standard "Standard for design of steel structures" GB 50017, and the concrete should comply with the relevant regulations of the current national standard "Code for design of concrete structures" GB 50010.

![Fig.1 Selection of steel and concrete specified by the codes](image)

Fig.1 shows that most steels use Q235, Q345, Q390, Q420, but high-strength and high-performance steels of Q460 and above are not in the scope of encouraging applications. At the same time, it is recommended that the strength of concrete is not less than C30, but the high-strength and super-high-strength concrete of C80~C100 is not in the encouragement range of wide application.

2.2 Regulations of steel pipe diameter -thickness ratio and size

Regarding the diameter -thickness ratio and dimensions of steel pipes, these codes give clear regulations, see Table 1 for details.

| Code name     | $D/t$          | $L/D$ or $d/l$ | $D_{min}$(mm) | $t_{min}$(mm) |
|---------------|----------------|----------------|----------------|----------------|
| GB 51367-2019 | -              | -              | 200mm          | 4              |
| JGJ 138-2016  | $D/t \leq 135(235/f_{ak})$ | -              | 400            | 8              |
| CECS 408:2015 | $D/t \leq 135(235/f_{a})$ | -              | 168            | 3              |
| GB 50936-2014 | $D/t \leq 135(235/f_{y})$ | -              | 168            | 3              |
| CECS 28:2012  | (20~135) $235/f_{y}$ | $\leq 20$ or $\leq 20$ | 200            | 4              |
| CECS 254:2012 | 20~100         | -              | 100            | 3              |
| JGJ 3-2010    | (20~100)$\sqrt{235/f_y}$ | -              | 400            | 8              |
| CECS 230:2008 | (20~90) $235/f_y$ | -              | 300            | 6              |
| CECS 188:2005 | $\leq 90(235)$ or $\leq 75(235)$ | -              | 200            | 6              |
| CECS 104-1999 | (20~135) $235/f_y$ | -              | -              | 8              |
Firstly, the specification only stipulates the minimum value of steel pipe size, and does not mention the maximum value of steel pipe diameter and wall thickness. And then, the length to diameter ratio of the component is limited to 20, which is equivalent to slenderness ratio no more than 80, which is the same as the building frame column in GB50017. Also, the limit range of steel pipe diameter-thickness ratio is 20~135, and the minimum wall thickness is 3~8mm. Finally, with the needs of engineering, the diameter and wall thickness of steel pipes are increasing, when the outer diameter, wall thickness, and diameter-to-thickness ratio of the steel pipe exceed the specification limits, the scope of application cannot be expanded at will. In-depth theoretical and experimental research should be carried out before supplementary regulations.

2.3 Regulations of confinement factor

The confinement factor is defined as

$$\theta = \frac{A_s f}{A_c f_c}$$

where $f$ and $f_c$ are the design value of steel strength and concrete strength respectively; $A_s$ and $A_c$ are the steel pipe area and the concrete area respectively. In Chinese current standards, the selection range of the confinement factor of concrete-filled steel tube members is basically limited to between 0.5 and 2.5.

3. Comparison of solid CFCST bearing capacity under axial compression

The design method of solid concrete-filled circular steel tube axially compressed components in China can be summarized into two theoretical systems: one is the unified theory, and the other is the limit equilibrium theory. Three of them adopt a unified theory, namely: CECS 408:2015, GB 50936-2014, CECS 254:2012; eight of them use limit equilibrium theory, which are: GB 51367-2019, JGJ 138-2016, GB 50936-2014, CECS 28:2012, JGJ 3-2010, CECS 230:2008, CECS 188:2005, CECS 104-1999.

3.1 Unified theory

The unified theory requires that the axial compression bearing capacity of single-limb concrete-filled steel tube members under a single force state should satisfy equations (1)–(9):

$$N \leq N_u$$ (1)

$$N_u = \varphi N_0$$ (2)

$$N_0 = A_{sc} f_{sc}$$ (3)

$$f_{sc} = (1.22 + B\theta + C\theta^2)f_c$$ (4)

$$A_{sc} = A_s + A_c$$ (5)

$$\alpha_{sc} = \frac{A_s}{A_c}$$ (6)

$$\theta = \frac{\alpha_{sc} L}{f_c}$$ (7)

$$\varphi = \frac{1}{2\lambda_{sc}} \left[ \frac{\lambda_{sc}^2}{\pi} \left( \Lambda_{sc}^2 + (1 + 0.25\lambda_{sc}) - \sqrt{\left( \Lambda_{sc}^2 + (1 + 0.25\lambda_{sc}) \right)^2 - 4\lambda_{sc}^2} \right) \right] (8)$$

$$\Lambda_{sc} = \frac{\lambda_{sc}}{\pi} \frac{f_{sc}}{E_{sc}} \approx 0.01\lambda_{sc}(0.001f_y + 0.781)$$ (9)

Where $N$, $N_u$, and $N_0$ are the design value of axial pressure acting on the component, the design value of the component axial compression stability bearing capacity, design value of the component axial compression strength bearing capacity. $A_{sc}$ and $f_{sc}$ are combined material cross-sectional area, $f$ and $f_c$ are the design values of steel compressive strength and concrete compressive strength respectively. Also, $\alpha_{sc}$ and $\theta$ are the steel content and the confinement factor related to the section of the member, B and C are the influence coefficients of the section shape on the confinement factor. What else, $\varphi$ is the stability coefficient of the axial compression member, $\lambda_{sc}$ and $\Lambda_{sc}$ are the slenderness ratio of the member and the regular slenderness ratio of the member respectively.

In the relevant three of these standards, the calculation requirements of CECS 408:2015 basically refer to GB 50936-2014. The difference between CECS 254:2012 and the former is the cross-sectional
strength of the combined material and the value of the stability coefficient. And the design value of the axial compression bearing capacity of the 3 is obtained by multiplying the axial compression strength bearing capacity and the stability factor. The calculation formula for the bearing capacity of the component is shown in Table 2.

| Number | Code name       | $A_{sc}(\text{mm}^2)$ | $f_{sc}(\text{N/mm}^2)$ | $N_0(KN)$ | $N_{u}(KN)$ |
|--------|-----------------|------------------------|--------------------------|------------|--------------|
| 1      | GB 50936-2014   | $A_s + A_c$            | $(1.212 + B\theta + C\theta^2)f_c$ | $A_{sc}f_{sc}$ | $\varphi N_0$ |
| 2      | CECS 408:2015   | $k_c k_s A_{sc} f_{sc}$ | $N_{u}$                 | $N_{u}$    |
| 3      | CECS 254:2012   |                        |                          | $N_{u}$    |

It can be seen from the table2 that CECS 408:2015 is the same as GB 50936-2014’s calculation formula for strength bearing capacity. Also, CECS 254:2012 calculation formula takes into account the effect of concrete creep and the cross-sectional strength of the reliability correction as the member’s strength bearing capacity, while GB 50936-2014 stipulates that when the permanent load of a solid axial compression member accounts for more than 50% of the total axial pressure, the stability bearing capacity of the member should consider the influence of concrete creep, and the influence coefficient is taken as 0.9. In conclusion, the difference of them is that one considers the influence of concrete creep in the calculation of the stability bearing capacity $N_{u}$, and the other considers the influence of reliability correction and concrete creep in the calculation of the strength bearing capacity of members $N_0$. In addition, the values of the stability coefficients in the two specifications are also different, which leads to different calculation results. At the same time, GB 50936-2014 composite material section strength $f_{sc}$ gives two solutions. The results show a linear increase with the rise of the steel content, and the calculated value is slightly higher than the look-up table value with an error of 2% to 6%.

### 3.2 Limit equilibrium theory

The limit equilibrium theory requires that the axial compressive bearing capacity of single-limb concrete-filled steel tube members should satisfy formulas (10)–(15):

$$N \leq N_u \quad (10)$$

$$N_u = \varphi_\theta \varphi_e N_0 \quad (11)$$

$$N_0 = 0.9 A_c f_c (1 + \alpha \theta) \quad (\text{when } \theta \leq \lbrack \theta \rbrack) \quad (12)$$

$$N_0 = 0.9 A_c f_c (1 + \sqrt{\theta + \theta}) \quad (\text{when } \theta > \lbrack \theta \rbrack) \quad (13)$$

And in any case: $\varphi_\theta \varphi_e \leq \varphi_0 \quad (14)$

$$\theta = \frac{A_{sc} f_{sc}}{A_s f_c} \quad (15)$$

Where $N, N_u$ and $N_0$ are the design value of the component axial pressure, the design value of the component axial compression bearing capacity, the design value of the component axial compression short column strength bearing capacity. $A_c$ and $f_c$ are the design values of the cross-sectional area and compressive strength of the core concrete in the steel pipe respectively. $A_{sc}$ and $f_{sc}$ are the design values of the cross-sectional area and compressive strength of the steel pipe respectively. $\alpha$ is the coefficient related to the concrete strength grade, $\theta$ is the confinement factor of the concrete-filled steel tube member. $\varphi_\theta$ and $\varphi_e$ are the bearing capacity reduction coefficients considering the influence of slenderness ratio and eccentricity respectively, and $\varphi_0$ is the value of $\varphi_\theta$ that considered as the axial compression member.

In the relevant 8 codes, the calculation methods of the coefficients related to the concrete grade, such as the section area of the member, the selection of material strength, and the confinement factor are the same. What differs is the calculation methods of the two influence coefficients. And the design value of the axial compression bearing capacity of the member is defined as the product of the short column strength bearing capacity design value and the two influence coefficients. The calculation formula for the bearing capacity of the member is shown in Table 3. Except for JGJ 138-2016 and CECS 188:2005, the calculation formulas for the strength and bearing capacity of short columns under
axial compression members are basically the same. The difference of the calculation results is mainly manifested in $\alpha$, $\varphi_t$ and $\varphi_e$.

Table 3 Formulas for axial compressive bearing capacity of equilibrium theory

| Number | Code name  | $N_0(KN)$ | $\varphi_t$ | $\varphi_e$ | $N_0(KN)$ |
|--------|------------|------------|-------------|-------------|------------|
| 1      | JGJ 138-2016 | When $\theta \leq [\theta]$: $N \leq 0.9 \varphi_t \varphi_e f_\alpha A_c (1 + \alpha \theta)$ | $\varphi_{t1}$ | $\varphi_{e1}$ | —          |
|        |            | When $\theta > [\theta]$: $N \leq 0.9 \varphi_t \varphi_e f_\alpha A_c (1 + \sqrt{\theta} + \theta)$ |            |            |            |
| 2      | GB 50936-2014 | $N = 0.9 f_c A_c (1 + \alpha \theta)$ | $\varphi_{t1}$ | $\varphi_{e1}$ | —          |
| 3      | CECS 28:2012 | When $\theta \leq 1/(\alpha - 1)^2$: $N = 0.9 f_c A_c (1 + \sqrt{\theta} + \theta)$ | $\varphi_{t1}$ | $\varphi_{e1}$ | —          |
| 4      | JGJ 3-2010   | $N = 0.9 f_c A_c (1 + \alpha \theta)$ | $\varphi_{t1}$ | $\varphi_{e1}$ | —          |
| 5      | CECS230:2008 | When $\theta > 1/(\alpha - 1)^2$: $N = 0.9 f_c A_c (1 + \sqrt{\theta} + \theta)$ | $\varphi_{t1}$ | $\varphi_{e1}$ | —          |
| 6      | CECS 104-1999 | $N = 0.9 f_c A_c (1 + \sqrt{\theta} + \theta)$ | $\varphi_{t1}$ | $\varphi_{e1}$ | —          |
| 7      | GB 51367-2019 | When $\theta \leq 1/(\alpha - 1)^2$: $N = 0.9 f_c A_c (1 + \alpha \theta)$ | $\varphi_{t1}$ | $\varphi_{e1}$ | —          |
|        |            | When $\theta > 1/(\alpha - 1)^2$: |            |            |            |
| 8      | CECS188:2005 | $N = 0.9 f_c A_c (1 + \sqrt{\theta} + \theta)$ | $\varphi_{t1}$ | $\varphi_{e1}$ | —          |

It is shown in Table 3 that there are three calculation methods for $\varphi_t$. The difference is that $\varphi_{t2}$ is more detailed than $\varphi_{t1}$ in calculation formula, but neither formula gives the upper limit of the aspect ratio, and $\varphi_{t3}$ is given by the look-up table and the maximum aspect ratio is 20. In addition, there are four formula modes for the eccentricity influence coefficient $\varphi_e$, and the difference lies in the large eccentricity calculation formula only.

3.3 comparison of stability coefficient

The calculation in this paper is based on the axial compression member with hinged ends, and the eccentricity influence coefficient in the limit equilibrium theory is taken as 1. The bearing capacity of all the codes differs in the value of the stability coefficient and the slenderness ratio influence coefficient mainly. The results of the calculation formulas given in GB 50936-2014, CECS 254:2012, JGJ 138-2016 and CECS230:2008 are shown in Figure 2.

![Fig.2 Comparison of $\varphi$ and $\varphi_t$](image)

It can be seen from Fig.2: (1) The main difference in the values of the four codes is the aspect ratio in the range of 4-40, and the stability coefficient of the unified theory is generally greater than the slenderness ratio influence coefficient of the limit equilibrium theory. (2) The length-to-diameter ratio of the member is restricted to less than 20, which is equivalent to $l/d \leq 80$, but the slenderness ratio of the two influence coefficients can be up to 250. (3) The calculation results of the difference in the range of length-to-diameter ratio 0~4, 4~20, 20~30, 30~40, and >40 for each specification are shown in Table 4.
Table 4 $\varphi$ and $\varphi_1$ difference percentage

| Range of $L/D$ | 0–4 | 4–20 | 20–30 | 30–40 | > 40 |
|---------------|-----|------|-------|-------|------|
| Mean          | 0.99| 0.83 | 0.58  | 0.40  | 0.21 |
| Variance      | 0.01| 0.13 | 0.13  | 0.07  | 0.06 |
| Maximum difference percentage | 4.10% | 64.07% | 64.07% | 33.37% | 18.75% |

4 Conclusion

(1) Due to its superior axial compression and low eccentric compression performance, the solid CFCST component exhibits a wide range of application prospects in axially stressed structural systems represented by "spatial grid structure, tower mast structure, and truss structure".

(2) Regarding the material and structure regulations of solid circular steel tube concrete, it is indicated that high-strength steel above Q460 and ultra-high-strength concrete above C100 are not in the scope of encouraged application. As the diameter of the steel tube and the material strength increases, the calculated difference in the strength and bearing capacity of the above-mentioned standard members becomes larger, if there is no basis to rely on, the scope of application must not be expanded at will and in-depth theoretical and experimental research is necessary.

(3) The current regulations in China have different provisions for calculating the bearing capacity of solid circular concrete filled steel tube axial compression members. The calculation difference mainly lies in the value of the stability coefficient and the slenderness ratio influence coefficient. There is a big difference in the length-to-diameter ratio range of 4-30, the maximum difference between the two coefficients is 64.07%, and the difference in the bearing capacity of the components is 62.79%.

(4) In the design of concrete-filled steel tube members, the current codes mostly stipulate that the diameter of the steel tube is not less than 200mm, and at the same time restrict its aspect ratio to not greater than 20, which is equivalent to restricting its slenderness ratio to less than 80. However, in the space latticed structure, the limit of the slenderness ratio of the compression bar is 180, and the diameter of the steel pipe is not clearly specified, and the calculation of the component bearing capacity is difficult to meet the current requirements of the concrete-filled steel tube specification. For the reinforcement method of infilled concrete in the reticulated shell structure, it is recommended that when the diameter of the steel pipe is 60-219, the concrete should be C50 or more, and when the diameter of the steel pipe is more than 219, the concrete can be C40 or more to meet the hoop rate of 0.5-2.5.

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