Constitutive relation of stiffened square CFST Columns

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Abstract. Using the constitutive model of a square CFST column with binding bars, the constrained mechanism of the stiffened square CFST columns is analyzed in great detail. The equivalent constitutive model under uniaxial compression is established for square CFST columns. The model is then used to describe the stress-strain curve process for concrete and to calculate the bearing capacity. Models of ten concrete-filled square steel tubular columns under axial compression specimens are created with constitutive relation. The results are compared with the axial compression test of an ordinary square CFST specimen column and stiffened square CFST specimens. Our results show that the bearing capacity and stress-strain curves under axial compression are consistent with the actual test measurements. Analysis can be applied to the square stiffened CFST columns, the square CFST columns with binding bars, and the ordinary square CFST columns.

1. Introduction

Researchers both at home and abroad have conducted numerous studies aimed to improve the performance of the square CFST short columns under axial compression¹⁻¹³. Cai Jian et al.¹⁻⁷ proposed a CFST short column with binding bars. They were responsible for a series of studies on the axial and eccentric compression performance. Susantha et al.⁸ proposed the structural form of stiffeners at the midpoint of the surrounding sides in a CFST column, and studied its buckling mode, bearing capacity, and ductility. Liang⁹, Liu¹⁰, and Uy¹¹ all investigated the local buckling of CFST columns.

Taken together, these researchers have proven that simple measures such as setting the binding bars and stiffeners can significantly enhance the concrete’s restriction. Likewise, the confinement effects are significantly improved, thus effectively delaying the local buckling of steel and improving bearing capacity.

The constitutive relationship of the confined concrete has been adopted to build the equivalent uniaxial constitutive relationship for the core concrete of each section. The above results of the
load-strain curves calculated by the proposed constitutive relationship are in good agreement with the experimental results.

The binding bars will appear to exhibit the elastic-plastic local buckling phenomena if the binding bars are only set. Thus the restriction of the internal concrete is weakened. Setting the stiffeners will increase still consumption but also prevent local buckling. Based on the results of CFST columns with binding bars and ribbed CFST columns under axial compression, this paper proposes a study of the stiffened square CFST short columns. This process does not significantly increase the need for more steel, while still effectively improving the lateral stiffness of square CFST columns.

2. Basic expressions of constitutive relationship

The constitutive relationship of the confined concrete was established using the Popovis stress-strain expression. The constitutive model shows concise expression and a clear mechanical concept. It also demonstrates how the constraint effects improve the ultimate strength; according to the concrete’s peak strain, there’s a noticeable phenomenon of gentle descending.

\[
\sigma_c = \frac{f_{co} \varepsilon_c}{r - 1 + x'} \quad (1)
\]

\[
x = \frac{\varepsilon}{\varepsilon_{cc}} \quad (2)
\]

\[
r = \frac{E_c}{(E_c - f_{co} / \varepsilon_{cc})} \quad (3)
\]

\[
\varepsilon_{cc} = \varepsilon_c [1 + \eta (\frac{f_{cc}}{f_{co}} - 1)] \quad (4)
\]

\[
f_{cc} = f_{co} (-1.254 + 2.254 \sqrt{1 + \frac{7.94 f_{fr}}{f_{co}} - 2 \frac{f_{fr}}{f_{co}}}) \quad (5)
\]

Where \(\sigma_c\) and \(\varepsilon\) respectively denote the axial stress and strain of concrete; \(f_{co}, \varepsilon_{co}\) and \(E_c\) are respectively the compressive strength, the corresponding strain, and the elastic modulus of unconfined concrete; \(f_{cc}\) and \(\varepsilon_{cc}\) respectively indicate the compressive strength, the corresponding strain, and elastic modulus of confined concrete for the stiffened square CFST columns. 

Reference[12,13] provides an example of how the calculation method can accurately assess the constitutive relationship of the square CFST columns with binding bars. Under the axial pressure, the steel pipe bears the longitudinal compression and lateral extrusion of concrete in the three-dimensional stress state of the longitudinal and radial compression and hoop tension. The hoop tension weakens the steel tubular vertical bearing capacity.

\[
f_a^2 - f_a f_{sr} + f_{sr}^2 = f_{fy}^2 \quad (6)
\]
The literature shows that the concrete filled square steel tube has a width thickness ratio parameter \( R \), where the steel tube is the main cause of failure.

\[
R = \frac{b}{t} \sqrt[4]{\frac{12(1-\nu^2)}{4\pi^2}} \frac{f_y}{E_y}
\]  

(7)

When \( R > 0.85 \), the specimen will sustain local buckling failure; when \( R \leq 0.85 \), the specimen will not encounter local buckling. In the above formula the value \( f_y \) may be determined by the following method.

When \( R > 0.85 \), with \( f_y = f_b \), the local buckling strength of steel tube \( f_b \) is given as:

\[
\frac{f_b}{f_y} = \frac{1.2}{R} - \frac{0.3}{R^2} \leq 1.0
\]

(8)

When \( R \leq 0.85 \), the value of \( f_y \) is determined according to the literature\(^1\). The literature\(^1\) obtained the relationship between \( n f_y \) and \( f_y \) after the regression of experimental data. It is similar with the recommended formula found in the AIJ design rules. Finally, by adopting the relationship types given by the recommended formula of AIJ rules, the following formula results:

\[
f_y = -0.21 f_y, f_y = 0.89 f_y
\]

(9)

In which, \( f_y \), \( E_y \), \( b \), \( t \) are respectively the yield strength of the steel tube, elastic modulus of steel tube wall, width of the cross-section, and steel tubular thickness.

According to the different stiffness ratio of the stiffener to plate, the buckling of the steel plate shows three forms: 1) Overall buckling: when the plate is thick, the stiffener is weak and the stiffness ratio is small. The stiffeners can only increase the stiffness of the steel plate. It cannot effectively constrain the outer surface deformation of the plate while the constrained plate is buckling overall at the same time. The elastic buckling strength of the structure improves as the stiffeners increase. 2) Local buckling: When the tubular wall is thin, and the stiffness ratio of the stiffener to plate is large, it shows the buckling of the small lattice. In this instance the stiffeners itself do not deform in lieu of playing the role of rigid boundary. As such the elastic buckling strength increases greatly. 3) Related buckling: exhibiting overall buckling while the local buckling occurs in the area of the small lattice. The buckling may occur when the stiffness ratio of the stiffener to plate lies between the local buckling and overall buckling, and in this case would belong to a critical buckling mode.

With regard to the square stiffened CFST columns, the set of the longitudinal and transverse stiffeners directly reduces the width to thickness ratio of the steel tubular wall. The longitudinal and transverse stiffeners limit the outer surface deformation of the steel plate. As such, the outer surface deformation is less than non-stiffened plates, and the lateral stiffness of the steel tubular wall increases.

The axial compression bearing capacity stiffening square CFST steel tubular short columns under may be calculated by increasing the binding effects of stiffeners on the basis of this. Based on the test results and constraint characteristics of the stiffener and taking into consideration the effects of bindings and vertical and horizontal stiffeners, we proceed with the assumption that the square CFST columns do endure local buckling before reaching the axial bearing capacity.

3. Test survey

| No. | \( b \) /mm | \( H \) /mm | \( t \) /mm | \( a_s \times b_s \times d_s \) /mm | \( b_h \times t_h \) /mm | \( b_p \times t_p \) /mm | \( b_y / t_y \) | arrangement of stiffeners |
|-----|-------------|-------------|-------------|-----------------|----------------|----------------|-------------|---------------------|
| C1  | 200         | 600         | 4           | 100×100×8       | 24×4.75        | 24×4.75        | 5.05        | outer transverse and inner longitudinal type |
| C2  | 200         | 600         | 4           | 100×100×8       | 20×5.73        | 20×5.73        | 3.49        |
| C3  | 200         | 600         | 4           | 100×100×8       | 30×3.75        | 30×3.75        | 8.00        |
4. Experimental verification of proposed constitutive relations

As shown in Fig.3, the contrast between the calculation curves and experimental curves (stress is the ratio of the axial force to the cross-sectional area of the specimens namely N/A; strain is the ratio of axial displacement to the height of the specimens namely, Δ/L).

It can be seen from Fig.3: the predict response to the development trend of the load are basically the same as the experimental curves; the peak load as calculated by the peak stress is approximate to the peak load of the test.
5. Conclusion

(1) The stiffened square CFST column is an improvement over the common square CFST column component. When compared to the square steel tube concrete column, due to the arrangement of stiffener, the constraint function of the binding bars is converted into a linear constraint, delay or complete avoidance of local steel tube buckling prior to reaching the ultimate bearing capacity. The constraint function of the tube on the core concrete is also improved, and thus the axial compression bearing capacity is greatly increased. In this way the specimen exhibited a stronger deformation performance.

(2) The stiffeners and binding bars cause the constrained action to be more complex; and the factors which impact the constitutive relationship of the core concrete are also more pronounced. Based on the constitutive relation of the confined concrete, taking the concept of the lateral equivalent effective stress, the author suggests the constitutive relationship of the core concrete under an axial compression. The constitutive relationship reflects the axial compressive performance of the core concrete. This is useful for stiffened square CFST columns as well as for square CFST columns with binding bars and common square CFST columns.
The proposed calculation method for the constitutive relation of CFST column can accurately determine the axial compression bearing capacity of the stiffened square CFST columns strength of axial compression.

Acknowledgments
The research described in this paper is part of the project entitled “Research on behavior of stiffened rectangular CFST”.

 Supported by Key scientific and technological project of Henan Province (No.182102310010); Key Scientific Research projects in Henan Province Universities (No.17A560023); Natural Science Foundation of Henan Province (No.182300410247).

The support is greatly appreciated.

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