Finite Element Analysis of the Mechanical Properties of Axially Compressed Square High-Strength Concrete-Filled Steel Tube Stub Columns Based on a Constitutive Model for High-Strength Materials

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Article

Abstract: With the development of new concrete technology, high-strength concrete has been used worldwide. In particular, more economic benefits can be achieved by applying high-strength concrete-filled steel tube (HSCFST) columns in the concrete core walls of super high-rise buildings. A constitutive relation with high applicability for high-strength materials with different strength grades is proposed. Based on this constitutive model, a brick element model of 181 sets of axially compressed square HSCFST members is established and experimentally verified. The effects of the concrete strength, diameter-to-thickness ratio, and steel yield strength on the axial compressive capacities of these members were investigated based on finite element calculation results. The results showed that with an increase in the concrete strength, the ultimate bearing capacities of CS-CC, HS-HC, HS-CC, and CS-HC stub column members increased by 60%, 24%, 44%, and 21% at most, respectively. Additionally, as the steel yield strength increased, the ultimate bearing capacities of CS-CC, HS-HC, HS-CC, and CS-HC stub column members increased by 8.8%, 5.1%, 8.5%, and 5.2%, respectively. Hence, material strength has the greatest impact on CS-CC and HS-CC. The confinement effect of the square steel tube on the concrete weakens as the strength grade of steel or concrete increases. Notably, the confinement effect of steel tube on the concrete is strongest in CS-CC and weakest in the CS-HC. In addition, the confinement coefficients of square HSCFST stub columns with different combinations of concrete and steel strengths were analyzed. Based on the superposition principle in the ultimate state, a practical axial compressive capacity calculation formula for three types of square HSCFSTs is established. Compared with existing major design code formulas, the proposed formula is more accurate and concise and has a clear physical meaning.

Keywords: high-strength concrete-filled square steel tube; finite element analysis; constitutive relation; confinement effect; bearing capacity calculation formula

1. Introduction

Due to their excellent structural properties, concrete-filled steel tube (CFST) columns have been widely applied in super high-rise buildings, urban bridges, long-span bridges, and engineering structures [1–3]. Compared with reinforced concrete columns, CFST columns have superior mechanical properties due to the interactions between the steel tube and the concrete. Specifically, in CFST columns, the three-dimensional compression of the concrete due to the confinement by the outer steel tube improves the compressive strength and deformation capacity of the concrete, and the lateral confinement of the concrete by the steel tube reduces the longitudinal stress of the steel tube in the ultimate...
state. Therefore, CFST columns have better flexural rigidity [4,5], bearing capacity [6], and seismic performance [7]. In addition, CFST columns have better fire [8] and corrosion resistance [9] due to the mutual protective effects of the steel tube and concrete. In practical engineering applications, the use of a CFST structure can significantly reduce the cross-sectional dimension of the columns, thereby reducing the material consumption by more than 50% [10]. CFST structures are easy to manufacture and weld on site and are convenient for concrete pouring with no need for formwork support [11].

In recent years, with the continuous development of materials technology, high-strength materials, such as high-strength steel (HSS), high-strength concrete (HSC), and ultrahigh-strength concrete (UHSC), have been gradually applied to engineering structures. HSS usually refers to steel with a nominal yield stress equal to or greater than 460 MPa [12]. Compared with normal-strength steel, HSS has the advantages of lower construction cost and greater environmental friendliness [13]. In addition, HSS is more suitable for lightweight, high-performance high-rise buildings and long-span structures due to its excellent strength-to-weight ratio, corrosion resistance, and welding performance. However, the application of HSS in practical engineering applications is limited due to the strict restrictions on steel strength grades and imperfect bearing capacity calculation formulas. Range and classification of HSC and UHSC have already been given by Sojobi et al. [14]. HSC has a compressive strength between 50 MPa and 90 MPa, and UHSC has a compressive strength of greater than 90 MPa. Although HSC and UHSC have far greater compressive strengths than normal-strength concrete, their higher brittleness and weaker ductility are not conducive to earthquake resistance and limit their applications in conventional concrete structures [15]. Despite the various restrictions in the application of high-strength materials, UHSC CFST column structures have been applied in the Abeno Harukas building in Osaka, the Star City complex in Sydney, and the Obayashi Technical Research Institute in Tokyo. These UHSC CFST column structures occupied less floor area due to their small cross-sectional areas, which resulted in an increased usable area and more economic benefits. Hence, HSCFST column structures have high research value and promising application prospects.

The steel tube has a lower confinement effect on the concrete, bearing capacity, and ductility in a square CFST column than in a circular CFST column, but square CFST columns are easy to connect and have large cross-sectional moments of inertia, high stability, and good adaptability in terms of earthquake and fire protection measures [16,17]. Researchers have carried out experimental, numerical, and finite element analysis studies on the mechanical properties and practical applications of square HSCFST columns. Yan et al. [18] conducted axial load tests on 32 square UHSC CFST stub columns. Their results showed that the confinement coefficient had a significant effect on the axial load–deformation curves of the specimens and that when the confinement coefficient was between 1.41 and 5.27, the specimens had good ductility. Lai [19] collected 124 sets of axial compression test data of HSCFSTs and compared them with the design method provided by the American Institute of Steel Construction (AISC) specification. Cai and Young [20] experimentally analyzed 26 square CFST stub columns (concrete strength: 34.9 MPa ≤fc ≤112.7 MPa, steel strength: 629 MPa ≤fs ≤1022 MPa) and conducted extensive numerical analyses on the confinement effect, material, geometry, and contact method. They also evaluated the applicability of the design codes for the compressive strengths of square and rectangular stub columns based on the test results and numerical calculation results. Existing studies have found that the interactions between the steel tube and concrete are related to the strength of the two materials. Therefore, it is necessary to propose formulas for calculating the confinement coefficient and the corresponding bearing capacity that take into account the effect of different material combinations based on the study of the HSCFST stub columns.

In this paper, three types of square HSCFSTs, namely, HSS tubes filled with normal-strength concrete (denoted as HS-CC hereinafter), HSS tubes filled with HSC (denoted as HS-HC hereinafter), and normal-strength steel tubes filled with HSC (denoted as CS-HC hereinafter) are used as the study object. The confinement coefficient of square HSCFST
stub columns and a calculation formula for their axial compressive capacity are proposed based on the uniaxial constitutive relation of HSS and concrete proposed by Ding et al. [21] as well as theoretical derivation, numerical simulation, and statistical analysis. The main steps are as follows: A test database (yield strength: 235–960 MPa, compressive strength of concrete: 30–185 MPa) was constructed by collecting the published axial compression test data of square HSCFST stub columns to verify the unified constitutive relation of steel and concrete with different strength grades. The three types of square HSCFSTs with different strength grades were analyzed to find the variation patterns of their confinement effects and the differences in their confinement efficiencies, such as the steel tube yield strength, the concrete strength grade, and the width-to-thickness ratio (steel content). Based on the results of the finite element analysis and static equilibrium theory, the confinement coefficients of the three types of square HSCFSTs were established and the practical bearing capacity calculation formula for the axially compressed square HSCFST stub columns is proposed.

2. Introduction to the Constitutive Relation of the Materials

2.1. Stress–Strain Relation for Steel

The uniaxial tensile stress–strain relation for steel proposed by Ding et al. [22] can be expressed as follows:

\[
\sigma = \begin{cases} 
E_s \varepsilon & \varepsilon \leq \varepsilon_y \\
 f_s & \varepsilon_y < \varepsilon \leq \varepsilon_{st} \\
 f_s + E_{st}(\varepsilon - \varepsilon_{st}) & \varepsilon_{st} < \varepsilon \leq \varepsilon_u \\
 f_u & \varepsilon > \varepsilon_u 
\end{cases}
\]  

where \( \sigma \) is the stress, \( E_s \) is the elastic modulus (\( E_s = 200 \text{ GPa} \)), \( f_s \) is the yield strength, \( f_u \) is the ultimate strength, \( \varepsilon_y \) is the yield strain, \( \varepsilon_{st} \) is the strain corresponding to the end of the yield plateau, \( \varepsilon_u \) is the ultimate strain, and \( E_{st} \) is the hardening modulus. Then, assuming that the stress of the steel remains constant as the strain increases, the stress–strain relation of the steel is shown in Figure 1. For HSS with no evident yield plateau, \( \varepsilon_{st} = \varepsilon_y \), as shown in Figure 1b.

![Figure 1. Uniaxial stress–strain curve of steel with or without yield plateau.](image-url)

The literature suggests that the \( \varepsilon_{st} \) of hot-rolled steel with a clear yield plateau should be 0.02 and that the \( f_u \) and \( \varepsilon_u \) of hot-rolled steel with different strength grades are expressed as follows:

\[
\frac{f_u}{235} = 0.86 \frac{f_y}{235} + 0.72
\]
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\[
\frac{\varepsilon_u}{\varepsilon_{u,235}} = \frac{1}{1 + 0.15(f_y/235 - 1)^{1.85}}
\]

where \(\varepsilon_{u,235}\) is the ultimate strength of Q235 carbon steel, where Q represents the yield limit of this material, and 235 refers to the yield stress being approximately 235 MPa.

Under axial compression, a CFST column is in a three-dimensional stress state due to the interactions between the steel tube and the core concrete. The equivalent stress \(\sigma_i\) and the equivalent strain \(\varepsilon_i\) are expressed as follows:

\[
\sigma_i = \sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2]}
\]

\[
\varepsilon_i = \sqrt{\frac{1}{2(1 + v_s)^2}[(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_1 - \varepsilon_3)^2 + (\varepsilon_2 - \varepsilon_3)^2]}
\]

where \(\sigma_1, \sigma_2, \text{and} \sigma_3\) and \(\varepsilon_1, \varepsilon_2, \text{and} \varepsilon_3\) are the principal stresses and strains, respectively, of the outer steel tube and vs. is the Poisson’s ratio of the steel tube, which is defined as follows:

\[
v_s = \begin{cases} 
0.285 & \varepsilon_i \leq 0.8\varepsilon_y \\
1.075(\sigma_1/f_y - 0.8) + 0.285 & 0.8\varepsilon_y < \varepsilon_i \leq \varepsilon_y \\
0.5 & \varepsilon_i > \varepsilon_y 
\end{cases}
\]

2.2. Uniaxial Stress–Strain Curve of the Core Concrete

A unified constitutive relation applicable to concrete with different strength grades has been previously proposed [22]. The stress–strain relation of the core concrete in a CFST column can be expressed as follows:

\[
y = \begin{cases} 
\frac{A_1 x + (B_1 - 1)x^2}{1 + (A_1 - 2)x + B_1 x^2} & x \leq 1 \\
\frac{x}{A_1(x-1)^2} & x > 1 
\end{cases}
\]

In the formula, the physical meaning of parameter \(A_i\) is the ratio of the elastic modulus to the peak secant modulus of the concrete, and \(B_i\) is a parameter that controls the degree of attenuation of the elastic modulus of the ascending segment of the stress–strain curve.

When concrete is subjected to uniaxial compression, \(y = \sigma / f_c\) and \(x = \varepsilon / \varepsilon_c\) in Equation (7), where \(\sigma\) is the stress in MPa, \(f_c\) is the axial compressive strength of concrete, \(f_c = 0.4f_{cu}^{7/6}\), \(\varepsilon\) is the strain, \(\varepsilon_c\) is the peak compressive strain, and \(\varepsilon_c = 420 f_{cu}^{7/18} \times 10^{-6}\). At this time, \(i = 1\), and \(A_1\) and \(B_1\) are the parameters of the ascending segment \((A_1 = 6.9, B_1 = 1.67(A_1 - 1)^2))\), and \(A_1\) is a parameter of the descending segment \((a_1 = 4\times 10^{-3}f_{cu}^{1.5}\) considering that the parameter of the descending segment is relatively low due to the high brittleness of concrete with a cube compressive strength exceeding 60 MPa).

To achieve the proposed stress–strain relation in the finite element model analysis, the Poisson’s ratio of the core concrete was defined as 0.2. The elastic modulus of concrete with different strengths is expressed as follows:

\[
E_c = 9500f_{cu}^{1/3}
\]

3. Finite Element Theoretical Analysis

Due to the limitations of experimental conditions and material properties, the large amount of collected HSCFST test data still cannot cover the parameter matching required for the study. Therefore, it is necessary to use the ABAQUS finite element calculation software for calculation and analysis. The interactions between the steel tube and core concrete can be rationally analyzed by adopting suitable element types and meshing, material properties (constitutive model), steel tube–concrete interface simulation, loading method, and boundary conditions.
3.1. Element Type and Meshing

Both the outer steel tube and the core concrete are analyzed using refined modeling with three-dimensional eight-node brick elements (C3D8R), and each node has three translational degrees of freedom. In the study of mesh convergence, the optimal finite element mesh is determined to provide a relatively accurate solution at a relatively low computation cost. Hassanein [23] noted that mesh refinement has little effect on the numerical results and confirmed that its effect on the N–e curve was negligible by testing the mesh convergence of the model with a coarse mesh. Therefore, the axial element size is selected to be 2.5 times the lateral element size. Based on the study of mesh convergence, the cross-sectional element size of the square column is set at $B/10$, where $B$ is the width of the square steel tube, as shown in Figure 2.

![Figure 2. Schematic diagram of model unit.](image)

3.2. Material Constitutive Model

The material constitutive model for compressed steel and concrete with different strength grades is proposed based on Section 2. The Poisson’s ratio of the elastic part of concrete under uniaxial compressive stress ranges from 0.15 to 0.22, and the representative values of Poisson’s ratio of concrete are 0.19 to 0.2 in the American Society of Civil Engineers (ASCE) Standards and 0.2 in the National Standards of China. Hence, the Poisson’s ratio ($\nu_c$) of concrete is set to 0.2 in the numerical simulation. The flow potential eccentricity $e$, the viscosity coefficient $\kappa$, and $f_{cc}/f_c$ are set at 0.1, 0.0005, 2/3, and 2/3, respectively. When the concrete strength is less than 100 MPa, the dilation angle is set to 40°, and when the concrete strength is greater than 100 MPa, the dilation angle is set to 30°. These parameter settings have been widely applied in finite element numerical simulations [24–26].

3.3. Interface Simulation

The interactions between the steel tube and concrete are usually simulated by the surface-to-surface contact technique. A contact surface pair composed of the inner surface of the steel tube and the outer surface of the core concrete is defined. A hard contact mode is set at the interface in the normal direction. This mode allows the interface to separate after stretching and disallows penetration after compression. The tangential contact can be simulated using the Coulomb friction model, with a friction coefficient of 0.5. There is almost no relative slip between the steel tube and the concrete of a stub column since they bear the load together. A rigid body loading plate with an elastic modulus of $1 \times 10^{12}$ MPa and a Poisson’s ratio of $1 \times 10^{-7}$ is set at the top of the column. The contact between the loading plate and the column is taken as a tie connection, with high stiffness and good convergence. Therefore, the loading surface is taken as the master surface, and the column surface contacting the loading surface is the slave surface.
3.4. Boundary Conditions and Loading Methods

The bottom surface of the CFST column member has a fixed boundary condition, the top surface of the member has a free boundary, and only the displacement of the loading end in the loading direction is allowed. A static uniform load is proportionally applied in several load increments in displacement control mode on the top of the loading plate using the improved Riks method in the ABAQUS library. Equilibrium iteration is performed at each load increment, and the equilibrium path is tracked in the load–displacement space. This method is a strong nonlinear analysis method often used in static analysis. Nonlinear geometric parameters are introduced to handle large displacement analysis. The finite element model is shown in Figure 3.

![Figure 3. Mesh size selection and schematic view of the FE model.](image)

3.5. Model Validation

Figure 4 shows the 181 sets of experimental data samples collected from the literature on CFST columns composed of steel tubes and concrete with different strength grades. The test database does not contain data samples of axially compressed stub columns with excessive steel content, excessively small diameter-to-thickness ratios, or excessively large slenderness ratios. Considering that the materials in the constitutive model used in this study are hot-rolled steel and plain concretes, the test database also does not contain axial compression test data samples of stub columns containing stainless steel, aluminum alloys, or concrete reinforced with other materials (steel fiber, carbon fiber) under axial compression.

It can be observed that the constructed database contains a diameter-to-thickness ratio ranging from 20–120, a steel yield strength ranging from 175–1100 MPa, and a concrete compressive strength ranging from 20–190 MPa, which covers the general interest of engineering practice and academic research. All the published experimental results and relevant HSCFST parameters are shown in Appendix A Table A1.

The strength distribution pattern of the test data points is shown in Figure 4b. Approximately 82% of the test data points are concentrated in concrete strengths of less than 100 MPa, and 66% of the test data points are concentrated in $D/t$ ratios $\in [20, 60]$. The concrete is categorized into normal-strength concrete ($f_{cu} < 100$ MPa) and HSC ($f_{cu} \geq 100$ MPa) according to the dilation angle, and the steel is categorized into normal-strength steel ($f_s < 500$ MPa) and HSS ($f_s \geq 500$ MPa) according to whether the steel has a yield plateau.
The finite element modeling method used in this paper is applied to compare and analyze the axial compression test results of the square HSCFST stub columns provided in the literature. The verification of the typical finite element model is shown in Figure 5, which compares the finite element simulation curve of a typical square CFST stub column under axial compression with the experimental results in the literature. The comparison of the analysis results in Appendix A Table A1 shows that the ratio \( \frac{N_{u,e}}{N_{u,FE}} \) of the measured ultimate bearing capacity \( N_{u,e} \) to the ultimate bearing capacity calculated based on the finite element model \( N_{u,FE} \) is 1.02, with a dispersion coefficient of 0.038. The \( N_{u,FE} \) values are generally in good agreement with \( N_{u,e} \), especially in the elastic stage, during which the measured and calculated curves basically overlap. Figure 5 compares the finite element simulation curves of typical square HSCFST stub columns under axial compression and the experimental curves obtained from the literature. Hence, the bearing capacity–strain curves calculated based on the finite element model are generally in good agreement with the experimental curves obtained from the literature. There are obvious differences in the descending section of the test curve of some specimens, as shown in Figure 5a,e,f. Due to the influence of various factors in the experiment, the material strength cannot be fully exerted. After reaching the limit state, local defects may appear between the steel tube and concrete, manifesting as a rapid decrease in bearing capacity and poor ductility. Since only experimental data can be collected from the literature, and the specific conditions of the specimen and experimental status can only be known from pictures, so the influence of various defects is not considered in the modeling, and there are differences between some test curves and the descending section of the finite element calculation curve. After comprehensive consideration, this modeling method is reasonable and reliable.

### 3.6. Parameter Analysis

In the finite element model, the width \( B = D \), length \( L \), and wall thickness \( t \) of the square HSS tube are set to 500 mm, 1500 mm, and 3, 6, or 10 mm, respectively. The steel content \( \rho_s \) is between 0.02 and 0.08, the yield strength of the steel \( f_s \) is 235, 345, 460, 550, 690, 780, or 960 MPa, and the cube compressive strength of the concrete \( f_{cu} \) is 40, 70, 100, 120, 150, or 180 MPa. To explore the optimal combination of concrete strength and tube strength, these concrete strength and steel yield strength values were paired up to form a total of 126 model groups, and the model parameters are shown in Table 1. In this paper, HSS tubes filled with HSC were denoted as HS-HC, HSS tubes filled with normal-strength concrete were denoted as HS-CC, normal-strength steel tubes filled with HSC were denoted as CS-HC, and normal-strength steel tubes filled with normal-strength concrete were denoted as CS-CC. The three types of HSCFSTs, namely, HS-HC, HS-CC, and CS-HC, are the focus of analysis in this paper.
Figure 5. Comparison of FE and experimental load–strain curves of HSCFST. (a) Test-SST1-A [27]; (b) Test-80804-C40-A [20]; (c) Test-1201204-C120-B [20]; (d) Test-S1 [28]; (e) Test-SC-32-80 [29]; (f) Test-SC-32-46 [29].

The effect of concrete strength on the mechanical properties of square HSCFST stub columns was analyzed using a steel tube wall thickness \( t \) of 6 mm and steel yield strengths \( f_y \) of 345, 460, 690, and 960 MPa. Figures 6–8 show the effect of different parameters on the axial compressive capacity of the square HSCFST stub columns. Specifically, the concrete strength grade, the steel yield strength, and the steel content all have a certain effect on the load–displacement curve and the bearing capacity.
Figure 6 shows the load–longitudinal strain (N–L) curves of axially compressed square HSCFST columns with different $f_{cu}$ values. The effects of concrete strength on the mechanical properties of axially compressed square HS-HC, HS-CC, CS-HC, and CS-CC stub column members with a tube wall thickness (t) of 6 mm and concrete strengths ($f_{cu}$) of 30, 60, 90, 120, 150, and 180 MPa were analyzed. The results show the following: (1) Under the premise that other parameters remain constant, the concrete strength $f_{cu}$ is one of the factors influencing the bearing capacity of the CFST members. The initial stiffness of the members is little affected by $f_{cu}$, and the ductility increases with increasing $f_{cu}$. (2) With an increase in the concrete strength, the ultimate bearing capacities of CS-CC, HS-HC, HS-CC, and CS-HC stub column members increased by 60%, 24%, 44%, and 21% at most.
respectively. Hence, the concrete strength has the greatest impact on CS-CC, the second greatest impact on HS-CC, and the least impact on CS-HC.

![Figure 6. Influence of concrete strength on the load–strain curve.](image1)

![Figure 7. Influence of steel yield strength on the load–strain curve.](image2)
3.6.2. Steel Yield Strength $f_s$

The effects of steel yield strength ($f_s$) on the load–displacement curves of axially compressed square HS-HC, HS-CC, CS-HC, and CS-CC stub column members with a tube wall thickness ($t$) of 6 mm and steel yield strengths ($f_s$) of 235, 345, 460, 550, 690, 800, and 960 MPa were analyzed, as shown in Figure 7. The analysis results show the following: (1) Under the premise that other parameters remain constant, the initial stiffness of the HS-HC, HS-CC, CS-HC, and CS-CC stub column members is almost the same, and the steel yield strength has almost no effect on the stiffness of the members. (2) The ultimate bearing capacity increases with increasing steel yield strength $f_s$, which indicates that the steel yield strength is one of the factors influencing the bearing capacity of the CFST members. As the steel yield strength increased, the ultimate bearing capacities of CS-CC, HS-HC, HS-CC, and CS-HC stub column members increased by 8.8%, 5.1%, 8.5%, and 5.2%, respectively. Hence, steel yield strength has the greatest impact on CS-CC and HS-CC, the second greatest impact on HS-HC, and the least impact on CS-HC.

3.6.3. Width-to-Thickness Ratio ($B/t$)

Figure 8a–d shows the load–displacement curves of the axially compressed square CFST columns with different width-to-thickness ratios. The analysis results of the square HS-HC, HS-CC, CS-HC, and CS-CC stub columns with $B = 500$ mm and $t = 6$ mm show the following: (1) Under the premise that other parameters remain constant, the ultimate bearing capacities of the members increase as the width-to-thickness ratio decreases. When the thickness $t$ decreased from 5 mm to 3 mm, the bearing capacities of HS-HC, HS-CC, CS-HC, and CS-CC stub columns increased by 14%, 24%, 5%, and 13%, respectively. Hence, the width-to-thickness ratio ($D/t$) has the greatest impact on HS-CC and the least impact on CS-HC. (2) Compared with concrete strength and the steel yield strength, the width-to-
thickness ratio has a greater impact on the initial stiffness of the members. The greater the width-to-thickness ratio of a member is, the greater the initial stiffness of the member.

In summary, the influence of material strength and width-thickness ratio on bearing performance is complex. In order to explore the best configuration, it is recommended to use the linear weighting and optimization method proposed by Sojobi [30], which is a simplified multi-criteria decision-making optimization method which can be utilized to select the best structural configuration when several configurations are considered alongside several mechanical properties.

3.7. Analysis of the Confinement Effect

The variation pattern of the longitudinal stress–strain curves and circumferential stress–strain curves of the steel tube used by Ding [11] can reflect the confinement effect of the steel tube on the concrete in a square CFST stub column under axial compression. The confinement effect of the steel tube on the core concrete can be assessed through the equivalent radial stress of the concrete under lateral compression: $\sigma_{r,c} = 2\kappa \theta_{p} / (B - 2t)$. The confinement efficiency of the steel tube on the core concrete can be evaluated by the radial confinement coefficient and the time at which the longitudinal stress–strain curve of the steel tube intersects its circumferential stress–strain curve. Figure 9 compares the axial compressive stress and radial confinement coefficient of the square HSCFST stub columns and the common-strength CFST stub columns. As shown in the figure, (1) as the steel strength grade increases, the radial stress of the core concrete ($\sigma_{r,c}$) decreases during the early loading stage but increases during the late loading stage, whereas the radial confinement coefficient ($\eta_c$) decreases constantly. (2) As the concrete strength grade increases, the $\sigma_{r,c}$ always decreases, whereas $\eta_c$ decreases in the early loading stage but increases at the late loading stage. (3) During the loading process, the longitudinal stress of the steel tube gradually decreases after reaching the maximum point, while the circumferential stress of the steel tube gradually increases after reaching the minimum point. The intersection point of the longitudinal stress–strain curve and the circumferential stress–strain curve of CS-CC appears first, while that of CS-HC appears last because the HSC has not reached the peak stress when the common-strength steel buckles. Hence, CS-HC has the weakest confinement effect.

![Figure 9](image-url)

Figure 9. Comparison of axial compressive properties between high-strength specimen and ordinary specimen.
4. Calculation Formula for Bearing Capacity

4.1. Model Simplification and Formula Establishment

The model is simplified using the superposition principle and stress distribution analysis. $A_c$ is the cross-sectional area of the concrete, $A_{c1}$ is the unconfined area of the concrete, $A_{c2}$ is the confined area of the concrete, $B$ is the cross-sectional length or width of the steel tube of each strength grade, and $t$ is the wall thickness of the steel tube of each strength grade. According to the stress distributions in Figure 10a–c, when the core concrete reaches the ultimate state, the relations between $A_c$, $A_{c1}$, and $A_{c2}$ are expressed as follows:

$$A_{c1} = 0.25A_c$$  \hspace{1cm} (9)

$$A_{c2} = 0.75A_c$$  \hspace{1cm} (10)

![Figure 10. Simplified stress distribution model at the mid-height section of CFST stub columns.](image)

Figures 11 and 12 show three points on the cross-sections of the steel tubes at the ultimate bearing capacities of the three types of HSCFST columns: the middle point b, the corner point a, and the 1/4 point c on the same side of the square. The ratio of the longitudinal stress ($\sigma_{L,s}$) to the nominal yield strength ($f_s$) of the steel tube and the ratio of the circumferential stress ($\sigma_{\theta,s}$) to the $f_s$ of the steel tube at these three points varies with the ultimate strength of the specimen ($f_{sc} = N_u/A_{sc}$, $A_{sc} = A_c + A_s$), as shown in the figures. When a square HSCFST stub column reaches its axial compressive capacity, the relation between the axial stress and the yield stress and the relation between the circumferential stress and the yield stress of the steel tube are as follows:

$$\sigma_{L,s} = \alpha f_s$$  \hspace{1cm} (11)
\[ \sigma_{\theta,s} = \beta f_s \]  

(12)

Figure 11. Average ratio of longitudinal stress to yield strength of a high-strength steel tube.

The relation between the radial stress of the core concrete and the circumferential stress of the steel tube shown in Figure 10 is as follows:

\[ \sigma_{r,c} = \frac{2t\sigma_{\theta,s}}{B} \]  

(13)

The relation between the axial compressive strength \( f_{L,c} \) and the lateral stress \( \sigma_{r,c} \) of the core concrete in the reinforced zone is as follows:

\[ f_{L,c} = f_c + 3.4\sigma_{r,c} \]  

(14)
Based on the static equilibrium condition of the cross-section, the following equation can be obtained:

\[N_u = \sigma_{L,c} A_c + f_{L,c} A_{c1} + \sigma_{L,s} A_s \quad (15)\]

According to Equations (11)–(15), the axial compressive capacity of the square HSCFST (\(N_u\)) can be expressed as follows:

\[N_u = f_c A_c + K \sigma_s A_s \quad (16)\]

where \(K\) is the confinement coefficient of the square steel tube to the concrete. Table 2 shows the \(K\) values of the three types of square HSCFSTs and the \(K\) values of the CS-CC obtained from the literature. The CS-CC has the best confinement effect among the
four types of CFSTs. Among the three types of square HSCFSTs, HS-CC has the best confinement effect, HS-HC has the second-best confinement effect, and CS-HC has the weakest confinement effect.

Table 2. Parameter value and comparison of steel constitutive model.

| Match Type | Formula | $\alpha$ | $\beta$ | $K$ | Quantity | Average FE | Dispersion FE | Average Equation (16) | Dispersion Equation (16) |
|------------|---------|---------|---------|-----|----------|-------------|----------------|------------------------|--------------------------|
| CS-CC      | $N_u = f_c A_c + K f_s A_s$ | 0.96    | 0.19    | 1.20 | 74       | 1.02        | 0.083          | 1.08                   | 0.043                    |
| HS-C C     | 0.87    | 0.21    | 1.14    | 68   | 1.06     | 0.96        | 0.083          | 0.98                   | 0.062                    |
| CS-HC      | 0.95    | 0.10    | 1.07    | 20   | 1.03     | 1.00        | 0.091          | 0.99                   | 0.058                    |
| CS-CC      | 0.97    | 0.07    | 1.06    | 19   | 1.00     | 1.00        | 0.065          | 1.02                   | 0.038                    |

4.2. Formula Verification

Figure 13 compares the axial compressive capacities of the three types of square HSCFSTs calculated using the axial compressive capacity calculation formula and the experimental results of previous studies. In Figure 1, the average stress $N/(A_s + A_c)$ is compared due to the large differences in the cross-sectional sizes of square CFST stub columns used in different axial compression tests. Table 2 shows the statistical results of the comparison between the measured bearing capacities and the bearing capacities calculated using Equation (16) or the finite element model. The bearing capacities calculated using Equation (16) or the finite element model are in good agreement with the measured bearing capacities, although the dispersion coefficient of Equation (16) is slightly larger.

![Figure 13. Comparison of experimental results with Equation (16) and FE, respectively.](image)

At present, Eurocode 4 (EC4)-2004 [31], the British standard BS5400 [32], the Chinese standard GB50936-2014 [33], and American ACI standards [34] are the major design codes for calculating the axial compressive capacity of CFST. The applicability of the ultimate axial compressive capacities calculated by the formulas recommended in these design codes is analyzed in this paper using a bearing capacity database consisting of the experimental data from the 181 sets of CFST stub columns established in the previous section, and the relevant statistical results are shown in Table 3 and Figure 14. The average ratio of the $N_{u,exp}$ to the $N_u$ calculated based on the EC4-2004 is 0.99, with a dispersion coefficient of 0.172. The average ratio of $N_{u,exp}$ to the $N_u$ calculated based on the BS5400 is 1.39, with a dispersion coefficient of 0.142. The average ratio of $N_{u,exp}$ to the $N_u$ calculated based on the ACI standard is 1.07, with a dispersion coefficient of 0.160. The average ratio of $N_{u,exp}$ to the $N_u$ calculated based on the GB50936-2014 is 1.17, with a dispersion coefficient of 0.552. The $N_u$ calculated based on Equation (16) is in best agreement with the $N_{u,exp}$.
Table 3. Summary of available formulas in well-known national codes.

| Reference | Formulas | Average Values  | Dispersion Coefficient |
|-----------|----------|----------------|------------------------|
|           |          | (N_{u,exp}/N_{u,ref}) | (N_{u,exp}/N_{u,ref}) |
| GB50936 (2014) | \( N_0 = (1.212 + 0.80 + C_0^2)f_cA_{c} \) \( \theta = \frac{A_c}{A_t} \) \( \eta = 0.25(3 + \frac{f_{c}'f_t'}{f_{c}}) \leq 1.0 \) \( \eta_s = 4.9 - 18.8\frac{f_{c}'}{17\sqrt{f_{c}}} \geq 1.0 \) \( \eta_t = \sqrt{\frac{N_{u,exp}}{N_{u,ref}}} N_{pl,Rk} = A_s f_y + A_c f_{c}' \) \( N_{cfr} = \frac{\pi^2}{N_{pl,Rk} A_c (0.85f_{c})} \) | 1.06 | 1.17 | 0.91 | 1.84 | 1.17 | 0.300 | 0.473 | 0.296 | 0.733 | 0.552 |
| EC4 (2004) | \( N_{EC4} = \eta_s A_s f_y + A_c f_{c}'(1 + \eta_s \theta \frac{f_{c}'}{f_{c}}) \) | 0.99 | 1.00 | 0.93 | 1.03 | 0.99 | 0.131 | 0.125 | 0.139 | 0.104 | 0.172 |
| BS 5400 (1979) | | | | | | | | | | | |
| ACI-318 (2011) | \( N_{u} = A_s f_y / \gamma_s + 0.675 f_{cu} A_s / \gamma_c \) \( N_{ACI} = A_s f_y + 0.85 f_{c}' A_c \) | 1.43 | 1.32 | 1.51 | 1.10 | 1.39 | 0.076 | 0.176 | 0.111 | 0.111 | 0.142 |

Figure 14. This is a figure. Schemes follow the same formatting. (a) Comparison of ultimate bearing stress obtained from test results and GB50936. (b) Comparison of ultimate bearing stress obtained from test results and EC4. (c) Comparison of ultimate bearing stress obtained from test results and ACI. (d) Comparison of ultimate bearing stress obtained from test results and BS5400.

5. Conclusions
(1) A refined 3D finite element model consisting of 181 sets of axially compressed square HSCFST members is established using the unified constitutive relation of steel and concrete.
(2) A total of 126 groups of examples were constructed to analyze the effects of the diameter-to-thickness ratio, concrete strength \( f_{cu} \), and steel strength \( f_s \) on the bearing...
capacity and confinement effect of the members. Increasing the steel yield strength and reducing the concrete strength will weaken the confinement efficiency of the steel tube to the concrete. Among the four types of CFSTs, CS-CC has the strongest confinement effect, while CS-HC has the weakest confinement effect. Compared with concrete strength and the steel yield strength, the width-to-thickness ratio has a greater impact on the initial stiffness of the members. The greater the width-to-thickness ratio of a member is, the greater the initial stiffness of the member.

(3) Based on the equilibrium condition, a practical formula considering the confinement coefficient for the ultimate bearing capacity of square CFST stub columns under axial loading with different material matches was proposed. The proposed formula shows a better calculation accuracy and clearer physical meaning of HSCFST compared with major code formulae.

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**Appendix A**

**Table A1.** Comparison between finite element calculation results and literature experimental results of high-strength concrete-filled square steel tube stub columns.

| Specimen Number | Literature | D × t × L/mm | fcu/MPa | fy/MPa | Nu,e/kN | Nu,FE/kN | Nu,Eq/kN | Nu,e/Nu,FE | Nu,e/Nu,Eq |
|-----------------|------------|--------------|---------|--------|---------|---------|---------|------------|------------|
| NS1             | [35]       | 186 × 3.5 × 558 | 40      | 300    | 1555    | 1628    | 1694    | 0.96       | 0.92       |
| NS7             |            | 246 × 3 × 738  | 47.5    | 300    | 3095    | 2918    | 3005    | 1.06       | 1.03       |
| NS13            |            | 306 × 3.9 × 918 | 47.5    | 281    | 4179    | 4281    | 5087    | 0.93       | 0.92       |
| NS16            |            | 306 × 3.9 × 918 | 58.75   | 281    | 4658    | 4985    | 5087    | 0.93       | 0.92       |
| S2              |            | 127 × 4.34 × 609.6 | 32.5    | 357    | 1095    | 1144    | 1220    | 0.96       | 0.90       |
| S3              |            | 127 × 4.55 × 609.6 | 29.75   | 322    | 1113    | 1189    | 1152    | 0.94       | 0.97       |
| S4              |            | 127 × 5.67 × 609.6 | 29.75   | 312    | 1202    | 1225    | 1310    | 0.98       | 0.92       |
| C10K6-1-6-1     | [36]       | 150 × 4.5 × 1855 | 80.00   | 379.8  | 1895    | 1758    | 1841    | 1.08       | 1.03       |
| C10K6-1-6-2     |            | 150 × 4.5 × 1855 | 80.00   | 379.8  | 1895    | 1758    | 1841    | 1.08       | 1.03       |
| C10K6-1-6-3     |            | 150 × 4.5 × 1855 | 80.00   | 379.8  | 1895    | 1758    | 1841    | 1.08       | 1.03       |
| C10K6-1-6-4     |            | 150 × 4.5 × 1855 | 80.00   | 379.8  | 1895    | 1758    | 1841    | 1.08       | 1.03       |
| C10K6-1-6-5     |            | 150 × 4.5 × 1855 | 80.00   | 379.8  | 1895    | 1758    | 1841    | 1.08       | 1.03       |
| C10K6-1-6-6     |            | 150 × 4.5 × 1855 | 80.00   | 379.8  | 1895    | 1758    | 1841    | 1.08       | 1.03       |
| C12K6-1-6-1     | [37]       | 150 × 4.5 × 1855 | 94.00   | 379.8  | 2066.1  | 1935    | 1984    | 1.07       | 1.03       |
| C12K6-1-6-2     |            | 150 × 4.5 × 1855 | 94.00   | 379.8  | 2066.1  | 1935    | 1984    | 1.07       | 1.03       |
| C12K6-1-6-3     |            | 150 × 4.5 × 1855 | 94.00   | 379.8  | 2066.1  | 1935    | 1984    | 1.07       | 1.03       |
| C12K6-1-6-4     |            | 150 × 4.5 × 1855 | 94.00   | 379.8  | 2066.1  | 1935    | 1984    | 1.07       | 1.03       |
| C12K6-1-6-5     |            | 150 × 4.5 × 1855 | 94.00   | 379.8  | 2066.1  | 1935    | 1984    | 1.07       | 1.03       |
| C12K6-1-6-6     |            | 150 × 4.5 × 1855 | 94.00   | 379.8  | 2066.1  | 1935    | 1984    | 1.07       | 1.03       |
| HSS1            | [38]       | 110 × 5 × 330  | 35      | 750    | 1836    | 1819    | 2024    | 1.01       | 0.91       |
| HSS2            |            | 110 × 5 × 330  | 35      | 750    | 1836    | 1819    | 2024    | 1.01       | 0.91       |
| HSS8            |            | 160 × 5 × 480  | 37.5    | 750    | 2868    | 2918    | 3127    | 0.98       | 0.92       |
| HSS9            |            | 160 × 5 × 480  | 37.5    | 750    | 2922    | 2964    | 3220    | 0.99       | 0.91       |
| CSC40SD8        | [39]       | 150 × 8.275 × 453 | 43.2    | 488.38 | 3500    | 3326    | 3188    | 1.05       | 1.10       |
| CSC50SD9        |            | 150 × 8.275 × 451 | 55.3    | 488.38 | 3575    | 3518    | 3381    | 1.02       | 1.06       |
### Table A1. Cont.

| Specimen Number | Literature | $D \times t \times L/mm$ | $f_{cu}/MPa$ | $f_{y}/MPa$ | $N_{u}/kN$ | $N_{u,FE}/kN$ | $N_{u,e}/kN$ | $N_{u,Eq}/kN$ | $N_{u,Ed}/N_{u,Eq}$ |
|-----------------|-----------|------------------------|-------------|------------|-------------|--------------|-------------|-------------|------------------|
| CR4-A-8         |           | 148 x 4.38 x 444      | 87          | 262        | 2108        | 2145        | 2211        | 0.98         | 0.95            |
| CR4-A-2         |           | 148 x 4.38 x 244      | 35.4        | 262        | 1153        | 1135        | 1201        | 1.02         | 0.96            |
| CR4-A-4-1       |           | 148 x 4.38 x 444      | 50.5        | 262        | 1414        | 1435        | 1501        | 0.99         | 0.94            |
| CR4-A-4-2       |           | 148 x 4.38 x 244      | 50.5        | 262        | 1402        | 1425        | 1501        | 0.99         | 0.93            |
| CR4-A-4-3       |           | 210 x 5.48 x 430      | 46          | 294        | 3183        | 2830        | 2961        | 1.10         | 1.07            |
| CR4-C-4-3       |           | 210 x 4.5 x 630       | 46          | 277        | 2713        | 2534        | 2637        | 1.07         | 1.03            |
| CR4-C-8         |           | 215 x 4.38 x 645      | 90.3        | 262        | 3837        | 4028        | 4221        | 0.92         | 0.91            |
| CR4-D-1-1       |           | 325 x 4.38 x 645      | 51.375      | 262        | 4950        | 5311        | 5457        | 0.93         | 0.91            |
| CR4-A-2         |           | 144 x 6.36 x 432      | 31.75       | 618        | 2572        | 2615        | 2831        | 0.98         | 0.91            |
| CR6-A-4-1       |           | 144 x 6.36 x 432      | 50.625      | 618        | 2808        | 2866        | 3082        | 0.98         | 0.91            |
| CR4-D-4-2       |           | 144 x 6.36 x 432      | 50.625      | 618        | 2765        | 2655        | 2871        | 1.04         | 0.96            |
| CR4-A-8         |           | 144 x 6.36 x 432      | 87          | 618        | 3399        | 3125        | 3342        | 1.09         | 1.02            |
| CR6-A-8         |           | 211 x 6.36 x 633      | 31.75       | 618        | 3920        | 5342        | 5663        | 1.08         | 1.02            |
| CR8-A-8         |           | 319 x 6.36 x 957      | 51.375      | 618        | 7780        | 7318        | 7698        | 1.09         | 1.02            |
| CR8-D-2-1       |           | 318 x 6.36 x 954      | 51.375      | 618        | 7473        | 7108        | 7598        | 1.05         | 0.98            |
| CR4-C-8         |           | 319 x 6.36 x 957      | 95.1        | 618        | 10357       | 10568       | 11060       | 0.98         | 0.94            |
| CR6-A-8         |           | 120 x 4.67 x 360      | 31.75       | 835        | 2819        | 2794        | 3039        | 1.01         | 0.93            |
| CR8-A-4-2       |           | 120 x 4.67 x 360      | 50.625      | 835        | 2957        | 2971        | 3216        | 1.00         | 0.92            |
| CR6-A-8         |           | 119 x 4.67 x 357      | 87          | 835        | 3318        | 3100        | 3343        | 1.07         | 0.99            |
| CR4-C-2         |           | 175 x 4.67 x 525      | 31.75       | 835        | 4210        | 4343        | 4707        | 0.97         | 0.89            |
| CR8-C-2         |           | 175 x 4.67 x 525      | 50.625      | 835        | 4542        | 4733        | 5097        | 0.96         | 0.89            |
| CR6-A-8         |           | 175 x 4.67 x 525      | 87          | 835        | 5366        | 5121        | 5485        | 1.05         | 0.98            |
| CR8-D-4-1       |           | 265 x 4.67 x 795      | 51.375      | 835        | 7117        | 7286        | 7841        | 0.98         | 0.91            |
| CR8-D-4-2       |           | 265 x 4.67 x 795      | 51.375      | 835        | 7172        | 7303        | 7860        | 0.98         | 0.91            |
| CR8-D-5         |           | 265 x 4.67 x 795      | 90.3        | 835        | 8990        | 8613        | 9171        | 1.04         | 0.98            |
| CR6-D-4-1       |           | 211 x 5.48 x 633      | 101.1       | 294        | 4733        | 4532        | 4950        | 0.99         | 0.91            |
| CR6-D-4-2       |           | 211 x 5.48 x 633      | 101.1       | 277        | 4371        | 4282        | 4694        | 1.02         | 0.93            |
| CR6-D-9         |           | 211 x 8.83 x 633      | 113.875     | 536        | 7008        | 7079        | 7008        | 0.99         | 0.95            |
| CR4-D-1-2       |           | 204 x 5.95 x 612      | 103.5       | 540        | 5303        | 5040        | 5035        | 1.02         | 0.99            |
| CR8-A-4-3       |           | 180 x 9.45 x 540      | 48.875      | 825        | 6803        | 6640        | 6587        | 1.02         | 1.03            |
| CR8-A-9         |           | 180 x 9.45 x 540      | 101.1       | 825        | 7402        | 6786        | 7402        | 1.09         | 0.93            |
| CR4-C-9         |           | 180 x 6.6 x 540       | 101.1       | 824        | 5873        | 5446        | 5873        | 1.08         | 0.91            |

**Notes:**
- [10]:
- [40]:
- [41]:
- [42]:
- [43]:
- $N_{u,Ed}$: Ultimate Design Strength
- $N_{u,Eq}$: Ultimate Equivalent Strength
- $N_{u,Ed}/N_{u,Eq}$: Ratio of Ultimate Design Strength to Ultimate Equivalent Strength

### Materials

- HSSC1
- HSSC2
- HSSC3
- HSSC4
- 80 x 80 x 4 C120-A
- 80 x 80 x 4 C80-B
- 80 x 80 x 4 C80-B
- 80 x 80 x 4 C120-B
- 100 x 100 x 4 C40-B
- 100 x 100 x 4 C80-B
- 100 x 100 x 4 C120-B
- 120 x 120 x 4 C40-B-r
- 120 x 120 x 4 C40-B
- 120 x 120 x 4 C80-B
- 120 x 120 x 4 C80-B
- 120 x 120 x 4 C120-B

**Table continued...**
### Table A1. Cont.

| Specimen Number | Literature | $D \times t \times L$ (mm) | $f_{u,\text{cu}}$ (MPa) | $f_{y,\text{cu}}$ (MPa) | $N_{u,e}$ (kN) | $N_{u,\text{FE}}$ (kN) | $N_{u,\text{EQ}}$ (kN) | $N_{u,e}/N_{u,\text{EQ}}$ | $N_{u,e}/N_{u,\text{FE}}$ |
|-----------------|------------|-----------------------------|-------------------------|------------------------|----------------|---------------------|---------------------|------------------------|------------------------|
| SC-32-80        | [30]       | 305 × 8.9 × 1200            | 120.00                  | 560                    | 14,116        | 14,401              | 14,116              | 0.98                   | 0.93                   |
| SC-48-80        |            | 305 × 6.1 × 1200            | 120.00                  | 660                    | 12,307        | 12,749              | 12,307              | 0.97                   | 0.86                   |
| SC-32-46        |            | 305 × 8.6 × 1200            | 120.00                  | 259                    | 11,590        | 10,942              | 11,590              | 1.04                   | 0.95                   |
| SC-48-46        |            | 305 × 5.8 × 1200            | 120.00                  | 471                    | 11,568        | 11,138              | 11,568              | 1.04                   | 0.91                   |

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