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Mechanical behavior of high-strength RPC filled circular and square steel tube considering size effect and interface bond

Qian Zhu[a]*, Shuan-hai He[b] & Jun-hai Zhao[a]

[a]School of Civil Engineering, Chang'an University, Xi'an 710061, China
[b]School of Highway, Chang'an University, Xi'an 710064, China

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With consideration of interface bonding performance and size effect, the unified solutions of bearing capacity for reactive powder concrete (RPC) filled circular and square steel tube are presented based on the unified strength theory (UST) and thick-walled cylinder theory. Parametric studies are carried out to investigate the influence of the unified strength theory parameter, confinement index and RPC strength. It is shown that proper choices of influential parameters are significant in the design of such components. The calculation formulas with regard for interface bond and size effect match better with the experimental data. Through the statistical analysis, the theoretical formula and the calculation method in the technical regulation is verified. Compared to the technical specifications, the proposed calculation formulas are more precise. It is concluded that the practical calculation formulas have an important practical value for the optimum design and engineering application of RPC filled steel tube.

Keywords: Mechanical behavior, High-strength RPC filled steel tube, Axial compression bearing capacity, Unified strength theory (UST), Size effect, Interface bond

High-strength reactive powder concrete (RPC) filled steel tubular composite structure has a widespread application prospect due to its high bearing capacity, desirable plastic toughness, excellent impact resistance and seismic performance[1,2]. This composite structure also has significant economic, environmental and social benefits in the consumption of resource conservation and the implementation of industrial waste reuse. The mechanical behavior of RPC filled steel tubular columns has been launched part of research work. But research on RPC filled steel tube in recent times was mainly focused on experimental investigation. RPC filled square steel tube has the disadvantage of unstable ultimate bearing capacity and is sensitive to local defects, so this study is less mature than RPC filled circular steel tube. Wu and Yao[3] investigated the experimental data of RPC filled circular steel tubular columns by a linear regression analysis, and deduced the expression of the ultimate bearing capacity. Tian *et al*.[4] worked out the relationship between load carrying capacity and confinement coefficient of RPC filled steel tube through processing and analysis of the test results by quadratic function fitting. Yan *et al*.[5] suggested the empirical formula of ultimate loading capacity for the RPC filled steel tube stub columns according to the statistical analysis of ultimate bearing capacity test data. Wu[6] conducted the axial compression experiments of 36 tests to determine the ultimate bearing capacity, but did not give the calculation method of RPC filled square steel tubular short column. Ji *et al*.[7] studied the influences of different slenderness ratio and hoop coefficient on RPC filled circular steel tube slender columns based on 14 specimens subjected to axial compression.

Study on ultimate bearing capacity of RPC filled steel tubular columns, much of literatures are based on the evaluation specification of common concrete filled steel tube or experimental results of regression analysis. Although the evaluation formulas are consistent with the test value, the statistical experimental data is limited and not universal. In addition, these empirical formulas have different expressions and parameters, which are not easy for the popularization and application. Theoretical analysis of RPC filled different cross-section steel tubular columns subjected to axial compression bearing capacity was conducted by using the unified strength theory and thick-walled cylinder theory. The amendment of core RPC compressive strength was

*Corresponding author (E-mail: zhuqianchd@126.com)

carried out by adopting the statistical size effect model. The modified formulas of external steel tube were conducted by introducing the plastic limit solution of thick-walled cylinder with size effect. Based on the above two correction formulas, the calculation formula of axial compression bearing capacity with size effect model and interfacial bonding strength is presented for RPC filled circular and square steel tubular stub columns. The accuracy of the ultimate capacity formula is effectively improved for high-strength RPC filled steel tubular composite columns. A number of parametric studies, including in strength theory parameter, confinement index and RPC strength are also discussed to investigate their effects on the analytical solutions.

Theoretical Method

Unified strength theory (UST)

The UST was established and developed based on orthogonal octahedron in a twin-shear element model[8,9]. It specifies that material fails when a function of the two larger principal shear stresses and their corresponding normal stresses reaches a certain limit value. The mathematical formula of UST is expressed as follows[8,9]:

$$F=\sigma_1-\frac{\alpha}{1+b}(b\sigma_2+\sigma_3)=\sigma_t \qquad \sigma_2\le\frac{\sigma_1+\alpha\sigma_3}{1+\alpha}$$
$$F'=\frac{1}{1+b}(\sigma_1+b\sigma_2)-\alpha\sigma_3=\sigma_t \qquad \sigma_2\ge\frac{\sigma_1+\alpha\sigma_3}{1+\alpha} \quad \dots (1)$$

where α and b are defined as $\alpha=\sigma_t/\sigma_c$, $b=\frac{(1+\alpha)\tau_s-\sigma_t}{\sigma_t-\tau_s}$;

F and F' are functions of principal stress strength theory; σ_1, σ_2 and σ_3 are the major, intermediate and minor principal stresses, respectively. Here, tensile stress is positive. σ_t, σ_c and τ_s are tensile, compressive and shear yield strength of the material, respectively; α denotes the tension-compression strength ratio and an index of the material S-D effect; b is the unified strength theory parameter that reflects the influence of the intermediate principal stress and also a parameter of failure criterion, with $0\le b\le 1$.

Thick-walled cylinder theory

The thick-walled cylinder is loaded by the internal pressure and the axial compression simultaneously. If $\sigma_1\ge\sigma_2\ge\sigma_3$, then $\sigma_1=\sigma_\theta>0$, $\sigma_2=\sigma_z$, $\sigma_3=\sigma_r<0$ (where $\sigma_r,\sigma_\theta,\sigma_z$ are the radial stress, circumferential stress and axial stress, respectively). The axial stress σ_z can be written as[8]: $\sigma_z=\frac{m}{2}(\sigma_r+\sigma_\theta)$. Where m is an intermediate principal stress coefficient, $0<m\le 1$. Its value can be determined by theory and experiment, where $m=2\nu$ (ν is the poisson ratio) in the elastic zone and $m\to 1$ in the plastic zone. Because of $\alpha\le 1$, the condition $\sigma_2\le\frac{\sigma_1+\alpha\sigma_3}{1+\alpha}$ should be adopted. Then Eq. (1) can be transmuted as

$$\frac{2+2b-\alpha bm}{2+2b}\sigma_\theta-\frac{\alpha bm+2\alpha}{2+2b}\sigma_r=\sigma_t \quad \dots (2)$$

Eq. (2) is the yield condition of thick-walled cylinder based on UST.

The thick-walled cylinder with internal radius r_i and external radius r_o is subjected to a uniformly supported pressure. $m\to 1$ is desirable in the plastic zone. In general, the common approximation is m=1, which corresponds to the plastic incompressible hypothesis. For anisotropic materials in tension and compression, the plastic limit pressure of thick-walled cylinder is formulated as[10]

$$p_p=\frac{\sigma_t}{1-\alpha}\left[\left(\frac{r_i}{r_o}\right)^{\frac{2(1+b)(\alpha-1)}{2+2b-\alpha b}}-1\right] \quad \dots (3)$$

where σ_t is the tensile yield limit of steel tube in one-direction compression; r_i、r_o are internal radius and external radius, respectively. But this formula Eq. (3) does not take into account the size effect of structure.

Study on Size Effect and Interface Bonding Performance

As ultra high strength concrete, the size effect of RPC is different from ordinary concrete, and its compressive strength size effect is more obvious[11]. The size effect has important engineering significance which is related to the assessment of material's true strength and bearing capacity. The interface bond between steel tube and RPC is a prerequisite to ensure the co-operation. The existence of bond stress makes the load transmission between steel tube and core RPC and establishes the working stress required for structural bearing. The existing formula of axial compression bearing capacity for concrete filled steel tubular column showed obvious size effect. The influence of size effect for concrete filled steel tube can be effectively reduced by introducing the size effect model[12,13].

Size effect model of RPC

Considering the impact of size effect for RPC, the amendment of core RPC compressive strength was carried out by adopting Weibull statistical size effect model[14]. It is obtained as follows:

$$f_{cy}=f_c\left(V/V_c\right)^{-1/(\omega_c+1)},\quad \omega_c=27 \quad \ldots (4)$$

where f_{cy} is the modified uniaxial compressive strength; f_c and V_c are the strength and volume of standard specimen, respectively; V is the volume of calculative specimen; ω_c is the Weibull coefficient.

Size effect amendment of external steel tube

The plastic analysis of thick-walled cylinder is carried out based on the strain gradient plastic theory[15]. The spatial gradient term of the effective plastic strain is introduced to predict the size effect of materials. The stress-strain relationship of linear-hardening materials takes the form as[16]

$$\sigma_e=\begin{cases}E\varepsilon_e & \sigma_e\le\sigma_y\\ \sigma_y+E_p\varepsilon_e^p-C\nabla^2\varepsilon_e & \sigma_e>\sigma_y\end{cases} \quad \ldots (5)$$

where E is the elasticity modulus; E_p is the tangent modulus of reflecting plastic hardening; σ_e and ε_e are the effective stress and effective strain, respectively; ε_e^p is the effective plastic strain; σ_y is the yield stress; C is the gradient coefficient; ∇^2 is the Laplace operator.

As for the plane strain elastic-plastic problem, it is satisfied $\sigma_z=\frac{1}{2}(\sigma_r+\sigma_\theta)$. According to the unified yield criterion, it is generated as[7]

$$\sigma_e=\frac{2+b}{2+2b}(\sigma_\theta-\sigma_r) \quad \ldots (6)$$

By assuming the thick-walled cylinder subjected to internal pressure p_i, the boundary condition can be given as

$$\left.\begin{aligned}&\text{when } r=r_i,\quad \sigma_r=-p_i,\ \varepsilon_e=D\\ &\text{when } r=r_c,\quad \sigma_r=-p_c,\ \varepsilon_e=\sigma_y/E\end{aligned}\right\} \quad \ldots (7)$$

where r_c is the elastic-plastic interface radius, with $r_i\le r\le r_c$ in the plastic zone and $r_c\le r\le r_o$ in the elastic zone; D is a constant; p_c is the elastic-plastic interface pressure. The equation of single curve hypothesis for hardened materials can be written as

$$\bar{\varepsilon}/\bar{\sigma}=\varepsilon_e/\sigma_e \quad \ldots (8)$$

By combining the equilibrium equation, strain coordination equation and constitutive equation under axisymmetric plane-strain condition, and utilizing Eqs (7) and (8), the following expression is determined as

$$d\sigma_r=\frac{2(1+b)}{r(2+b)}\left[\sigma_y(1-\frac{E_p}{E})+E_pD\frac{r_i^2}{r^2}-4CD\frac{r_i^2}{r^4}\right]dr \quad \ldots (9)$$

By integrating Eq. (9) from r_i to r and with the boundary condition Eq. (7), The formula above can be manipulated as

$$\sigma_r=-p_i+\frac{2(1+b)}{2+b}\left[\sigma_y(1-\frac{E_p}{E})\ln\frac{r}{r_i}+\frac{E_pD}{2}(1-\frac{r_i^2}{r^2})-\frac{CD}{r_i^2}(1-\frac{r_i^2}{r^4})\right] \quad \ldots (10)$$

According to the continuity condition at the elastic-plastic interface and utilizing Eq. (10), the plastic limit internal pressure of thick-walled cylinder can be established as

$$p_s=\frac{2(1+b)}{2+b}\sigma_y\left[(1-\frac{E_p}{E})\ln\frac{r_o}{r_i}+\frac{E_p}{2E}(\frac{r_o^2}{r_i^2}-1)-\frac{C}{E}\frac{r_o^2}{r_i^2}(1-\frac{r_i^4}{r_o^4})\frac{1}{r_i^2}\right] \quad \ldots (11)$$

Equation (11) is the unified solution of plastic limit pressure for thick-walled cylinder with consideration of size effect, which is not only related to the ratio of inner and outer radius, but also associated with the inner and outer radius. Consequently, the feature size of the cylinder is introduced to consider the impact of size effect.

Influence of bond on bearing capacity

The transmission of interface forces and compatible deformation are realized by the interface bond action between steel tube and RPC, while previous studies assumed that the strain between two kinds of materials is completely continuous. It is necessary to consider the bond-slip effect for RPC filled steel tubular stub columns[17]. As an important part of the interaction between steel tube and core RPC, the bond strength is an important parameter for the engineering application for RPC filled steel Tube. The expression of bond stress is formulated as[17]

$$\tau=\mu p \quad \ldots (12)$$

where μ is the friction coefficient. Its value is related to the characteristics of steel tube and concrete materials, which is 0.6 according to Ref.[18].

Calculation Formulas of Axial Compressive Bearing Capacity

Calculation formula for RPC filled circular steel tube

The section shape of RPC filled circular steel tubular column is shown in Fig. 1.

According to thick-walled cylinder theory, the longitudinal compressive strength of circular steel tube can be written as

$$\sigma_z = \frac{1}{2}(\sigma_r + \sigma_\theta) = \frac{p_1 r_i^2}{r_o^2 - r_i^2} \quad \dots (13)$$

where p_1 is the lateral constraint force of circular steel tube.

Core RPC is under three-dimensional stress state, i.e. $0 > \sigma_1 = \sigma_2 > \sigma_3$. Based on the UST, stress of core concrete is formulated as follows[10]:

$$\sigma_3 = f_c + k\sigma_1 \quad \dots (14)$$

where k is the increasing coefficient of concrete strength, its value varies from 1 to 3[19]; σ_3 is the compressive strength of three-dimensional stress state, i.e., f_c'; f_c is the uniaxial compressive strength of RPC; σ_1 is the lateral pressure, i.e., p_1. By substituting these above equations into Eq. (14), then Eq. (14) can be transmuted as

$$f_c' = f_c + kp_1 \quad \dots (15)$$

The bearing capacity N_{u1} of composite column is undertaken by external steel tube and core RPC together. Its expression of RPC filled circular steel tubular short columns is obtained as

$$N_{u1} = N_c + N_s = f_c' A_c + \sigma_z A_s \quad \dots (16)$$

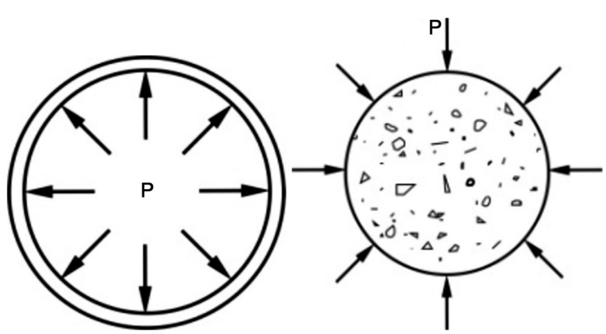

Fig. 1 — Force diagram of circular steel tube and core RPC

By substituting Eqs (13) and (15) into Eq. (16), the unified solutions can be established as

$$N_{u1} = (f_c + kp_1)A_c + \frac{r_i^2 p_1}{r_o^2 - r_i^2} A_s \quad \dots (17)$$

where A_c is the cross-sectional area of core RPC, defining $A_c = \pi r_i^2$; A_s is the cross-sectional area of circular steel tube, defining $A_s = \pi(r_o^2 - r_i^2)$.

Calculation formula for RPC filled square steel tube

The restraining zone of square steel tube to its core concrete can be divided into effective confinement area and non-effective confinement area, and the dividing line is a parabola, as shown in Fig. 2. The weakening of the lateral constraint on the non-effective restraining zone is represented by the influence factor, i.e., $\gamma_u = 1.67 D_c^{-0.112}$, where γ_u is the concrete strength reduction factor and D_c is the inner diameter of equivalent circular steel tube.

The equivalent constraint reduction factor δ is introduced, which denotes the proportional length constrained on one side of square steel tube, and considers the influence of thickness-side ratio ω, where ω is defined as $\omega = t_s/B$, with the wall thickness t_s and the outer side length B, as shown in Fig. 3. The calculated length l acting on the corner with uniform internal pressure can be expressed as $l = \delta B/2$. The lower corner non-uniform confinement force in Fig. 3 is equivalent to its upper corner uniform confinement

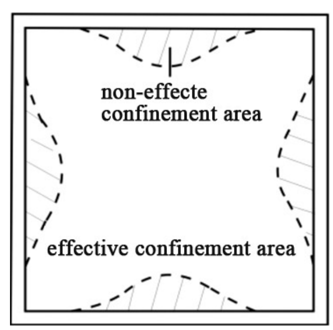

Fig. 2 — Effective confinement area of RPC filled square steel tube

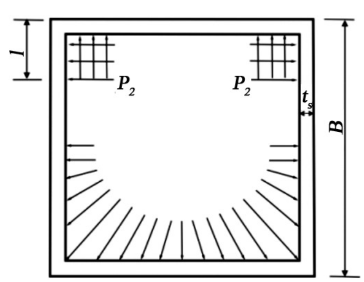

Fig. 3 — Internal pressure of RPC filled square steel tube

force, where p_2 means the uniform internal pressure at the corner of concrete filled square steel tube and reflects the fact that the failure of RPC filled steel tube is due to the plastic yield at the steel tubular corner and the local instability of the middle pipe wall. The internal pressure p_2 is defined as $p_2=\delta p_1$, where p_1 is the uniform internal pressure of equivalent concrete filled circular steel tube. The expression of δ can be established as[20]

$$\delta = 66.4741\omega^2 - 0.9919\omega + 0.41618 \quad \ldots (18)$$

According to the equal-area method, the steel and concrete area of RPC filled square steel tubular column is transformed into the equivalent steel and concrete area of RPC filled circular steel tubular column. By utilizing the calculation formula $B^2=\pi r_o^2$ and $(B-2t_s)^2=\pi r_i^2$, the expression of r_o、r_i is generated as

$$r_o = B/\sqrt{\pi}\,,\quad r_i = (B-2t_s)/\sqrt{\pi} \quad \ldots (19)$$

where B is the outer side length of square steel tube; t_s is the wall thickness of square steel tube; r_o and r_i are the external radius and internal radius of equivalent circular steel tube, respectively.

The unified solutions of ultimate bearing capacity N_{u2} for RPC filled square steel tube can be indicated as

$$N_{u2} = N_s + N_c = \sigma_{zp} A_s + \gamma_u \sigma_{cp} A_c \quad \ldots (20)$$

where A_s and A_s are the sectional area of steel tube and core RPC, respectively, defining $A_s = 4Bt_s - 4t_s^2$ and $A_c = (B-2t_s)^2$; σ_{zp} and σ_{cp} are the longitudinal compressive strength of steel tube and core RPC in three-dimensional stress state, respectively.

The longitudinal compressive strength σ_{zp} and σ_{cp} can be obtained in terms of UST and thick-walled cylinder theory as follows:

$$\sigma_{zp} = \frac{p_2 r_i^2}{r_o^2 - r_i^2} = \frac{\delta p_1 r_i^2}{r_o^2 - r_i^2}\,,\quad \sigma_{cp} = f_c + kp_2 = f_c + k\delta p_1 \quad \ldots (21)$$

By substituting Eq. (21) into Eq. (20), the expression of N_{u2} is transmuted as

$$N_{u2} = (4Bt_s - 4t_s^2)\frac{\delta p_1 r_i^2}{r_o^2 - r_i^2} + \gamma_u (B-2t_s)^2 [f_c + k\delta p_1] \quad \ldots (22)$$

where r_o and r_i are obtained by Eq. (19); p_1 is obtained by Eq. (3).

Interface bond and size effect amendment of axial compression bearing capacity

When considering the bond stress on the steel tube and RPC interface, the steel tube is not only subjected to longitudinal pressure, but also the longitudinal bonding force. Using Eq. (12) and Eq. (13), the longitudinal stress of steel tube with bond effect can be written as

$$\sigma_{zb} = \frac{p_1 r_i^2}{r_o^2 - r_i^2} + \mu p \quad \ldots (23)$$

The compressive strength amendment of core RPC and external steel tube are carried out by adopting Eq. (4) of f_{cy} and Eq. (11) of p_s to substitute for the formulas of f_c and p_1 in Eq. (17) and Eq. (22), respectively. The modified formulas of axial compression bearing capacity with interface bond and size effect for RPC filled circular and square steel tubular short column can be deduced as

$$N'_{u1} = \left[f_{cy} + p_s - f_{cy}(0.96 - \sqrt{0.92 + (\frac{6}{f_{cy}} + \frac{1}{7})p_s}) \right] A_c + (\frac{p_s r_i^2}{r_o^2 - r_i^2} + \mu p_s) A_s \quad \ldots (24)$$

$$N'_{u2} = \delta(4Bt - 4t_s^2)(\frac{p_s r_i^2}{r_o^2 - r_i^2} + \mu p_s) + \gamma_u (B-2t_s)^2 [f_{cy} + k\delta p_s] \quad \ldots (25)$$

Where

$f_{cy} = f_c(V/V_c)^{-1/(\omega_c+1)}$, $\omega_c=27$; $\delta=66.4741\omega^2-0.9919\omega+0.41618$, $\omega=t_s/B$;

$$p_s = \frac{2(1+b)}{2+b}\sigma_t \left[(1-\frac{E_p}{E})\ln\frac{r_o}{r_i} + \frac{E_p}{2E}(\frac{r_o^2}{r_i^2} - 1) - \frac{C}{E}\frac{r_o^2}{r_i^2}(1-\frac{r_i^4}{r_o^4})\frac{1}{r_i^2} \right]$$

Results and Discussion

Comparison with technical specification

As for calculation of ultimate bearing capacity for concrete filled steel tubular members, the relevant technical specifications at home and abroad are mainly as follows: European EC4(1996), Japanese AIJ(1997), American LRFD(1994) and some domestic representative design specifications, such as CECS 28: 90(1992), DL /T 5085-1999 and so on. According to the relevant Refs[3,4,21,22], the bearing capacity of more than 80 specimens is verified in terms of the above specifications. The ratio of calculated value N_c and experimental value N_e is shown in Fig. 4. On

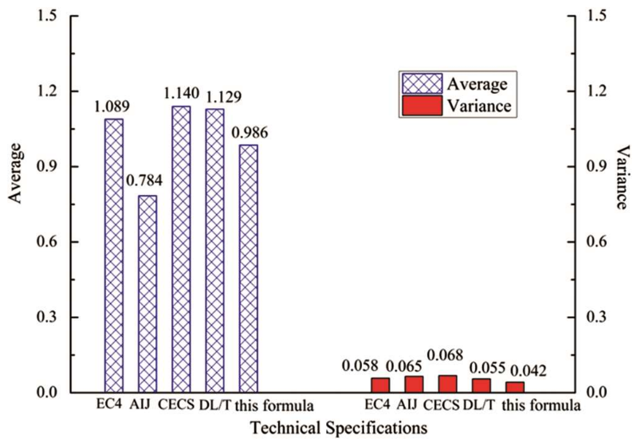

Fig. 4 — Comparison of statistical values of calculation results N_u/N_c

observing Fig.4, it can be seen that the calculated value is slightly larger than the test value, most of the specifications overestimate the ultimate bearing capacity of RPC filled steel tube (except that the calculation of AIJ code is too safe). The proposed practical formula in this paper is in most agreement with the experimental value.

Calculation example analysis

Taking the example of RPC filled circular steel tubular column in Ref.[3]: where the cross-sectional area of circular steel tube is A_s =2583 mm^2; the cross-sectional area of core RPC is A_c=11310 mm^2; the yield strength of steel is f_y=318 MPa; the uniaxial compressive strength of RPC is f_c=109 MPa; the external diameter of steel tube is D=133 mm; the wall thickness is t_s=6.5 mm. Then the ultimate bearing capacity of this composite column is calculated as N'_{u1}=2512.8kN .

Validation of calculation formula

The values of E and E_p in Eq. (11) for steel are set to E=2.03×10^5 MPa and E_p =6100 MPa, respectively. Wen *et al*.[16] indicated the relationship between the gradient coefficient C and the elasticity modulus E with defining the material characteristic length $l_0 = \sqrt{|C|/E}$. The characteristic length of steel is l_0=5.2 μm[23], then the gradient coefficient takes the value of C=-5.49 N.

The value ranges of k and b are as follows: k =1~3 (Ref.19), b =0~1 (Ref. 8), which value is set as k =2 and b =0.5 in this paper. The formulas can degenerate into the Mises failure criterion solutions when k =2 and b =0.5. According to the experimental data in Refs[3,6], the comparison of ultimate bearing capacity obtained in this paper Eq. (17) and Eq. (24), Eq. (22) and Eq. (25) with the experimental data is shown in Tables 1 and 2. As can be seen from Table 1, the calculation results with regard for interface bond and size effect match better with the experimental data. It is illustrated that the calculation method through the size effect modification of external steel tube and core RPC is feasible based on the UST and the bond-slip theory.

Based on the experimental data in Ref.[3,6,21,22], the ultimate bearing capacity of 84 specimens are analyzed statistically in terms of Eqs (17) and (24), as shown in Fig. 5. From Fig. 5, it can be observed that the calculation results without interface bond and size effect obtained by Eq. (17) are obviously larger than experimental data with the increase of diameter, whereas the trend of calculated values with interface bond and size effect obtained by Eq. (24) larger than experimental values is significantly reduced with the increase of diameter. It is demonstrated that the calculation method and calculation accuracy have an obvious improvement considering interface bond and size effect for RPC filled steel tube.

Parametric study

Figure 6 shows the influences of strength theory parameter b on the ultimate bearing capacity N'_u . The selection of parameter b represents various strength theories. Different b values correspond to different materials, i.e., UST can be applied to a variety of materials. The parameter b has a great influence on the ultimate bearing capacity of RPC filled steel tubular short column. In observing Fig. 6, it can be observed that the bearing capacity increases with the parameter b. N'_u is increased by 13.1% (for k=2), when b=1 compared with b=0. It is indicated that the strength latent potentials of materials are better achieved due to considering the effect of intermediate principal stress.

Figures 7 and 8 indicate the ultimate bearing capacity N'_u versus the confinement index ξ and RPC strength f_c, where ξ *is* defined as $\xi=(f_yA_s)/(f_cA_c)$. As show in Fig. 7, the bearing capacity increases with the parameter ξ. This is because the constraint effect of steel tube on core RPC enhances with an increasing ξ value, so as to improve the loading capacity of component. To investigate the effects of RPC strength f_c on the bearing capacity N'_u, the value of f_c is set to 100 MPa, 125 MPa and 150 MPa, as shown in Fig. 8. It illustrates that the growth of N'_u value is obvious with an increasing RPC strength.

Table 1 — Comparison of calculation results and experimental data for RPC filled circular steel tube

No.	$D \times t_s \times L$ (mm)	f_y (MPa)	f_c (MPa)	V_c (mm^3)	ξ	N_e (kN)	N'_{u1} (kN)	N_{u1} (kN)	N'_{u1} / N_e	N_{u1} / N_e	Note
1	133×3×400	290	109	3000000	0.257	2000	1932.2	1930.6	0.966	0.964	Ref.[3]
2						2005	1932.2	1930.6	0.964	0.961	
3	133×3×400	290	154	3000000	0.182	2300	2489.6	2500.4	1.082	1.087	
4						2350	2489.6	2500.4	1.059	1.064	
5	133×4.5×400	318	109	3000000	0.439	2250	2223.7	2191.6	0.988	0.974	
6						2200	2223.7	2191.6	1.011	0.996	
7	133×4.5×400	318	154	3000000	0.311	2700	2713.2	2734.8	1.005	1.013	
8						2750	2713.2	2734.8	0.987	0.994	
9	133×6.5×400	318	109	3000000	0.666	2300	2512.8	2441.0	1.093	1.061	
10						2350	2512.8	2441.0	1.069	1.039	
11	133×6.5×400	318	154	3000000	0.472	2950	3010.4	3249.6	1.020	1.104	
12						2950	3010.4	3249.6	1.020	1.104	
13	133×8.5×400	290	109	3000000	0.837	2500	2435.6	2726.4	0.974	1.090	
14						2550	2435.6	2726.4	0.955	1.069	
15	133×8.5×400	290	154	3000000	0.592	2950	2980.6	3201.7	1.010	1.085	
16						2960	2980.6	3201.7	1.007	1.082	
17	133×10×400	376	109	3000000	1.329	3200	3215.1	3074.7	1.005	0.961	
18						3100	3215.1	3074.7	1.037	0.990	
19	133×10×400	376	154	3000000	0.941	3450	3556.3	3565.7	1.031	1.034	
20						3450	3556.3	3565.7	1.031	1.034	
21	133×12×400	336	154	3000000	1.067	3500	3435.8	3598.0	0.982	0.999	
22						3650	3435.8	3598.0	0.941	0.958	
$\overline{X}$									1.011	1.046	
$\overline{W}$									0.0397	0.0601	

where $\overline{X}$ and $\overline{W}$ are the average. (24), respectively; N_e is the experimental data.

Table 2 — Comparison of calculation results and experimental data for RPC filled square steel tube

No.	$D \times t \times L$ (mm)	f_y (MPa)	f_c (MPa)	V_c (mm^3)	ξ	N_{shi} (kN)	N'_{u2} (kN)	N_{u2} (kN)	N'_{u2} / N_{shi}	N_{u2} / N_{shi}	Note
RA-1	100×4×300	207	80.3	3000000	0.429	925	1018.0	1038.9	1.101	1.123	Ref.[6]
RA-2	100×6×300	173	80.3	3000000	0.548	1725	1728.1	1150.8	1.002	0.667	
RA-3	100×10×300	233	80.3	3000000	1.270	2553	2235.3	2239.8	0.876	0.877	
QA-1	100×4×300	207	99.8	3000000	0.345	1023	1181.0	1202.8	1.154	1.176	
QA-2	100×6×300	173	99.8	3000000	0.441	1830	1777.6	1301.4	0.971	0.711	
QA-3	100×10×300	233	99.8	3000000	1.030	2125	2359.6	2365.6	1.110	1.113	
QB-1	100×4×300	207	87.9	3000000	0.392	1352	1281.5	1102.8	0.948	0.816	
QB-2	100×6×300	173	87.9	3000000	0.501	1800	1786.4	1209.5	0.992	0.672	
QC-3	100×10×300	233	87.9	3000000	1.170	2410	2283.7	2288.8	0.948	0.950	
$\overline{X}$									0.995	0.901	
$\overline{W}$									0.087	0.189	

where N_{u2} and N'_{u2} are the calculation results in Eqs (22) and (25), respectively; N_{shi} is the experimental data.

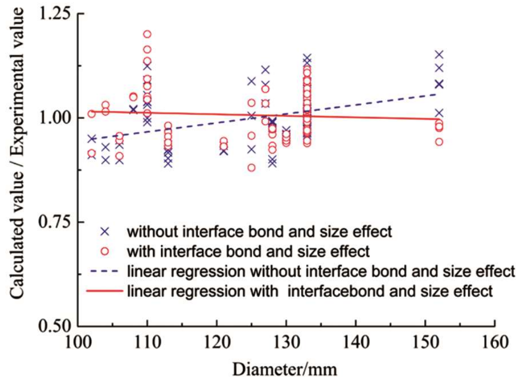

Fig. 5 — Comparison of calculation results

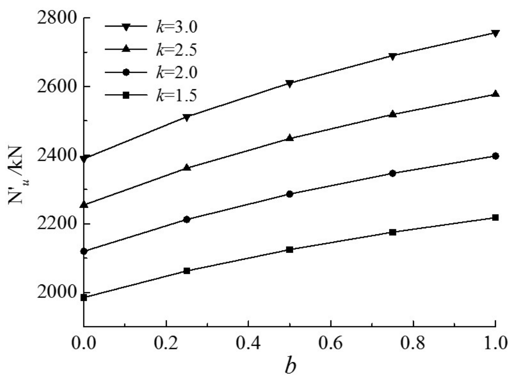

Fig. 6 — $N_u^{'}$ versus the coefficient b

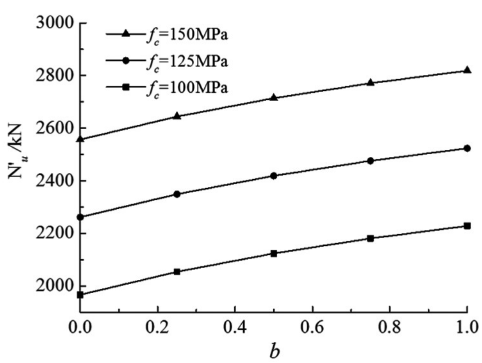

Fig. 7 — $N_u^{'}$ versus the coefficient ξ

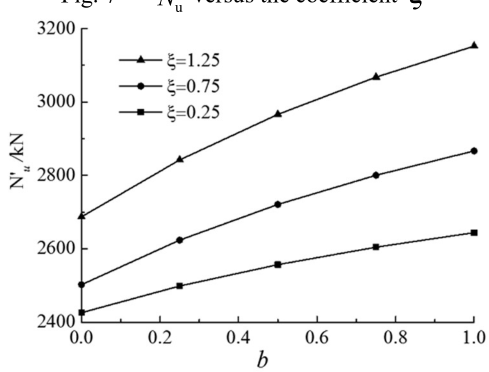

Fig. 8 — $N_u^{'}$ versus the coefficient f_c

Conclusions

The following conclusions are drawn from this study:

(i) Based on the unified strength theory(UST) and thick-walled cylinder theory, selecting the appropriate size effect model for RPC and adopting the strain gradient plasticity theory for external steel tube, the calculation formula considering size effect and interfacial bond is presented for RPC filled circular and square steel tubular short columns subjected to axial compression bearing capacity.

(ii) The axial compression bearing capacity of RPC filled steel tubular short column has a significant size effect. The calculation results without interface bond and size effect are obviously larger than experimental data with the increase of diameter, whereas the accuracy of calculation formula is effectively improved by the modification for RPC filled steel tube.

(iii) The ultimate bearing capacities of RPC filled steel tube are calculated by the national technical specifications, which are compared with the theoretical formula and the test results. It is shown that the present design regulations are not suitable for RPC filled steel tube, and the practical formula proposed in this study is in better agreement with the experimental data.

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