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Numerical Study on Confinement Effect and Efficiency of Concentrically Loaded RACFRST Stub Columns

Yicen Liu[1], **Fei Lyu**[1]*, **Faxing Ding**[1,2]*, **En Wang**[1], **Yunlong Xu**[1], **Tao Yuan**[3], **Chao Deng**[4] and **Chen Luo**[5]

[1]School of Civil Engineering, Central South University, Changsha, China, [2]Engineering Technology Research Center for Prefabricated Construction Industrialization of Hunan Province, Hunan Province, China, [3]Hunan Architectural Design Institute Co.Ltd, Changsha, China, [4]Hunan Academy of Research Co.Ltd, Changsha, China, [5]China Construction Fifth Engineering Division Corp.Ltd, Changsha, China

Edited by:
Yan-Bo Wang,
Tongji University, China

Reviewed by:
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Tongji University, China
Yunchao Tang,
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Zhibin Wang,
Fuzhou University, China

***Correspondence:**
Fei Lyu
lyufei@csu.edu.cn
Faxing Ding
dinfaxin@csu.edu.cn

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The mechanical behaviors of recycled aggregate concrete (RAC) are upgraded by outer steel tube confinement, and the performance of recycled aggregate concrete-filled steel tubular (RACFST) columns is similar to that of the traditional concrete-filled steel tube (CFST) columns. The purpose of this study is to investigate the behaviors of recycled aggregate concrete-filled rectangular steel tubular (RACFRST) stub columns under axial loading. Three-dimensional finite element (FE) models were established, which utilized a triaxial plastic-damage constitutive RAC model considering the replacement ratio of recycled aggregates. The finite element analysis results indicated that the lessened ultimate bearing capacity of RACFRST stub columns compared with their traditional concrete infilled counterparts was mainly due to the weakened confinement effect and confinement efficiency. A simplified formula of the bearing capacity of concentrically loaded RACFRST stub columns was proposed. The cross-sectional stress nephogram was reasonably simplified by the limited state of infilled concrete. The basics of proposed formula were the equilibrium condition and the superposition method. Finally, the formula for the bearing capacity of RACFRST stub columns was evaluated by comparing its accuracy and feasibility to some design formulae proposed by specialists and some design codes of different regions.

Keywords: recycled aggregate concrete-filled rectangular steel tubular stub columns, finite element analysis, ultimate bearing capacity, confinement effect, confinement efficiency

INTRODUCTION

With the rebuilding and expansion of cities, the vast construction of demolitions debris and the increasing construction material demand are becoming a social and environmental hotspot. Nowadays, construction demolition waste amounts to 40% of all kinds of waste according to some estimates (Xiao et al., 2012). Considering the protection of the environment and the sustainable development of construction industry, the researchers pay more attention to the environmental-friendly building materials, for instance, green concrete including green high-performance concrete (GHPC), recycled aggregate concrete (RAC), smart concrete and so on. Researchers have conducted a large number of experiments on the mechanical properties of RAC that use waste concrete as a substitute for coarse aggregate, which reveal the RAC with the low compressive strength (Li et al., 2006), tensile strength (Tabsh and Abdelfatah, 2009; Liu et al., 2011), shear strength (Tabsh and

Abdelfatah, 2009; Liu et al., 2011) and elastic modulus (Dong et al., 2016; Chen et al., 2017); high water absorption (Dong et al., 2016), drying shrinkage (Tam et al., 2014), creep (Tam et al., 2014) and peak compressive strain (Yang et al., 2020) and inferior durability (Dong et al., 2019) due to the microstructure of RAC is much more complicated than that of the traditional concrete and the weak interfacial link composed of many porosities and cracks caused by the existence of residual mortar attached to the previous concrete aggregate (Dong et al., 2016; Yang et al., 2020). Thus, the RAC was only applied in non-load-bearing structures or subordinate structures such as human-made mountain landscapes, the separation wall, and subgrade and basement in road construction. Aiming to expend the applications of RAC, researchers found that the combination of NAC and other materials to create hybrid material can improve the mechanical performances of NAC effectively. Incorporating the crumb rubber particles into RAC can restrain the crack development, decrease the porosity and improve the relative compressive strength of RAC under high-temperature environment (Tang et al., 2021). The steel-reinforced concrete structures showed that steel and concrete composite structure has good mechanical properties, and some scholars applied the steel reinforcement to RAC structures to improve the mechanical properties of RAC structures (Ma et al., 2013; Ma et al., 2015; Ma et al., 2019). The experiment results indicate that the RCA replacement percentage had no apparent influence on the ultimate bearing capacity of RAC structural components (Ma et al., 2013; Ma et al., 2015). However, the construction process of steel-reinforced recycled concrete columns is complicated and time-consuming since its equipment includes profile steel, longitudinal bars and stirrups (Dong et al., 2019) and the cross-sections of high-rise construction columns are enormous. Consequently, it is necessary to seek an effective and efficient way to improve the undesirable mechanical properties of RAC.

Concrete-filled steel tube (CFST) columns have been widely applied in modern construction projects and such type of composite columns has aroused the interests of engineers and scholars for its high strength and stiffness (Tam et al., 2019), excellent seismic performance and good fire resistance (Chen Z. et al., 2014). The surrounding steel tube contributes to the strength of structural members and encases the infilled concrete, which eliminating the formwork of concrete and saving the construction time. Learning from CFST, the performance of RAC can be improved with the use of steel tubes to form a composite structure (Dong et al., 2016) since concrete can be significantly affected by the lateral pressure (Huang et al., 2012) and the extension of internal microcracks can be effectively restricted (Tam et al., 2019). Meanwhile, infilling RAC into steel tube can avoid moisture loss (Tam et al., 2014), increase its compressive strength, and reduce its peak compressive strain, shrinkage and creep (Wang et al., 2015).

Konno et al. (Konno et al., 1988) found that the deformational behavior of the recycled aggregate concrete-filled steel tubular (RACFST) columns was similar to those of normal concrete (NC) counterparts. Still, the fracture development of RACFST columns was faster than that of NC counterparts, which leads to the ultimate bearing capacity and stiffness of the RACFST columns were smaller than the NC specimens. Shi et al. (Shi et al., 2010) investigated the strength and ductility of the RACFST columns. It was concluded that the ultimate strength of the RACFST columns was lower than that of the CFST columns filled with NC, and the RACFST columns with more extensive recycled aggregate replacement displayed higher deformation and better ductility. Yang and Zhu (Yang and Zhu, 2009) and Yang et al. (Yang et al., 2009) carried out studies on the cyclic behavior of RACFST beam-columns. The experimental results showed that the strength and stiffness of the RACFST specimens are slightly lower than those of the specimens with NC.

However, some researchers found that the relationship between the ultimate bearing capacity of RACFST and recycled aggregate replacement percentage is erratic (Zhang et al., 2012). Chen et al. (Chen Z. et al., 2014) found that RACFST columns with higher RCA replacement percentage had greater strength, and Mohanraj et al. (Mohanraj et al., 2011) reported that the average strength of RACFST specimens is larger than NC specimens.

Meanwhile, researchers found that other restraint materials (such as fiber-reinforced polymer (FRP) and glass-fiber-reinforced polymer (GFRP)) can benefit the compression behavior of the RACFST columns in order to broaden the structural applications of RACFST columns (Tang et al., 2020b).

To compensate for limitations of test research, FE analysis mainly performs nonlinear analysis, parameter analysis, and failure process analysis on structures or components (Dong et al., 2016). Ding et al. (Ding et al., 2011) proposed a triaxial plastic-damage constitutive model of concrete which is applied in CFST columns (Ding et al., 2018a) and structures' (Ding et al., 2020) FE model, and the results of FE models are in good agreement with the experimental data. Researchers (Dong et al., 2016; Yang et al., 2020) used the ABAQUS software to obtain the deformation characteristic, destruction characteristics and stress distribution nephogram of composite columns. Previous research results on FE analysis are positive and reliable. To dynamic real-time detect the surface deformation and full field strain in recycled aggregate concrete-filled steel tubular columns, Tang proposed mathematical models combining the four-ocular visual coordinates and point cloud matching (Tang et al., 2019). The four-ocular vision system can reconstruct the three-dimensional (3D) CFST model under complex loading, which is critical for evaluating the seismic performance and 3D deformation of the specimen (Tang et al., 2020a).

In this research, FE analysis was performed on 300 RACFRST stub columns based on experimental results. The verified FE models accurately predict the load-strain curves stress and ultimate bearing capacity. Then, a parametric study was carried out to investigate the effects of RAC strength, steel tube strength, steel ratio, replacement ratio of recycled aggregate and aspect ratio of cross-section on the axial compressive behavior of columns. Furthermore, the different confinement effect between concrete-filled square steel tubular (CFSST) and recycled aggregate concrete-filled square steel tubular (RACFSST) stub columns was compared. A simplified formula is proposed for the ultimate bearing capacity of RACFRST stub columns based on the superposition method. Finally, the comparison was made between the proposed formula's predicted results and some well-known design methods.

FINITE ELEMENT MODELING OF RACFRST STUB COLUMNS

Modeling Method

Nonlinear FE models for RACFRST stub columns under axial compression were established using the commercially available FE package ABAQUS version 6.14 (ABAQUS, 2014). In these models, the 8-node reduced integral format 3D solid element (C3D8R) was chosen to model the steel tube, infilled RAC, and the loading plate. Xiang et al. (Xiang et al., 2016) proposed that the mesh size of $B/10$ is the most suitable for the square RACFSST columns, where B is the length of the RACFSST columns. In order to identify the optimal mesh size, an investigation for the mesh sensitivity was carried out. The range of mesh size in this study is from $B/15$ to $B/5$, where B is the length of the RACFRST columns. The comparison of calculated ultimate bearing capacity of different mesh size was shown in **Supplementary Figure S1**. $N_{\mathrm{u},\ B/15}$, $N_{\mathrm{u},\ B/10}$, $N_{\mathrm{u},\ 3B/20}$ and $N_{\mathrm{u},\ B/5}$ represent the ultimate bearing capacity of $B/15$, $B/10$, $3B/20$ and $B/5$ mesh size series, respectively. The results revealed that the predicted results of models with $B/10$ mesh are similar with those with $B/15$ mesh. However, the predicted results of the models with larger mesh size ($3B/20$ and $B/5$) are relatively inaccurate. Considering the accuracy of the prediction results and the computation time of the model, the mesh size of $B/10$ and the structured meshing technique are adopted in the FE models. The mesh generation and boundary conditions of the FE model are shown in **Supplementary Figure S2**.

In the FE models, a surface-to-surface contact was adopted for the interaction of steel tube and infilled RAC, in which the inner surface of the steel tube was the master surface. In contrast, the external surface of the infilled RAC was chosen as the slave surface. The limited-slip was used in the sliding formulation while the discretization method was surface-to-surface. Tangential behavior and normal behavior were used in the contact property to simulate the bond-slip action between the steel tube and infilled RAC. The normal behavior was set to "hard" contact mode, allowing the separation after contact occurred. The penalty function was utilized to the friction formula for the tangential behavior, in which the friction coefficient was 0.5. A tie constraint can couple two separated surfaces so that no relative motion occurs between them. Therefore, the tie option was chosen to connect the upper surface of the steel tube and infilled RAC to the bottom surface of the loading plate so that the axial load can be applied simultaneously to the steel tube and infilled concrete on the whole loading process. The loading plate was selected as the master surface, and the top surface of the steel tube and infilled recycled concrete was the slave surface. The loading plate was simulated as a rigid body in which the elastic modulus was $1.0 \times 10^{12\circ}$MPa, and the Poisson's ratio was 1.0×10^{7}.

Constitutive Relation of Infilled Recycled Aggregate Concrete

Ding et al. (Ding et al., 2014) proposed a triaxial plastic-damage constitutive RAC model under concentrically loading, which was adopted in the established FE models. This triaxial plastic-damage constitutive RAC model was developed based on a triaxial plastic-damage constitutive model of NC (Ding et al., 2011) and exploited in a current study (Hu, 2014). This model accurately incorporated the influence of the replacement ratio of recycled aggregates on the mechanical behaviors of RAC under axial loading and can be expressed as:

$$y = \begin{cases} \dfrac{A_{1(r)}x + \left[B_{1(r)} - 1\right]x^2}{1 + \left[A_{1(r)} - 2\right]x + B_{1(r)}x^2} & x \le 1 \\ \dfrac{x}{\alpha_{1(r)}\left(x - 1\right)^2 + x} & x > 1 \end{cases} \tag{1}$$

$$\begin{cases} A_{1(r)} = \dfrac{(1 - 0.3r)(1 + 0.2r)}{(1 - 0.1r)} \times 9.1 f_{cu}^{-4/9}, B_{1(r)} = 5\left(A_{1(r)} - 1\right)^2 \big/ 3 \\ y = \sigma \big/ f_{c(r)}, x = \varepsilon \big/ \varepsilon_{c(r)}, \alpha_{1(r)} = 2.5 \times 10^{-5} f_{cu}^{3} \\ f_{c(r)} = (1 - 0.1r) f_c, f_{cu\ (r)} = (1 - 0.1r) f_{cu}, f_c = 0.4 f_{cu}^{7/6} \\ \varepsilon_c = 383 f_{cu}^{7/18} \times 10^{-6}, \varepsilon_{c(r)} = (1 + 0.2r)\varepsilon_c, E_{c(r)} = (1 - 0.3r)E_c, E_c = 9500 f_{cu}^{1/3} \end{cases} \tag{2}$$

Where r is the replacement ratio of recycled aggregates, $A_{1(r)}$ is the ratio of the initial tangent modulus to the secant modulus at peak stress, $B_{1(r)}$ is a parameter that controls the decrease in the elastic modulus along the ascending branch of the axial stress-strain relationship. $\alpha_{1(r)}$ is a descent stage parameter, and $\alpha_{1(r)}$ can be taken as 0.15 for confined concrete structures (Ding et al., 2014). The diagram of confined and unconfined plastic-damage model of RAC are shown in **Supplementary Figure S3**. In the compressive zone, y and x are the stress and strain ratio of the infilled RAC to the uniaxial compressive RAC, respectively. σ and ε are the stress and strain of the infilled RAC, respectively. $f_{\mathrm{c}(r)}$ is the uniaxial compressive strength of RAC, and the f_{c} is the corresponding uniaxial compressive strength of concrete with the replacement ratio of recycled aggregate is 0. $f_{\mathrm{cu}(r)}$ is the compressive cubic strength of RAC. The f_{cu} is the regular counterpart when the replacement ratio of recycled aggregate is 0. ε_{c} is the strain corresponding with the peak compressive stress of concrete, and the RAC counterpart is $\varepsilon_{\mathrm{c}(r)}$. E_{c} is the elastic modulus of normal concrete, and the RAC counterpart is $E_{\mathrm{c}(r)}$ (Ding et al., 2014). The relationship between $f_{\mathrm{c}(r)}$, $f_{\mathrm{cu}(r)}$, $\varepsilon_{\mathrm{c}(r)}$, $E_{\mathrm{c}(r)}$ with different recycled aggregate replacement ratio and the normal concrete counterparts is based on the abundant test results of RAC, theoretical analysis of RAC, the method of statistical analysis and the mechanical model of normal concrete.

The triaxial plastic-damage constitutive model of RAC was based on the stress-strain relation of RAC under uniaxial stress, and combined with the parameters of concrete strength criterion under multi-axial stresses and other parameters defined below. The eccentricity is 0.1; the ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress (f_{b0}/f_{c0}) is 1.225; the ratio of the second stress invariant on the tensile meridian to that on the compressive meridian is 2/3; the viscosity parameter is taken as 0.005, and the dilation angle is 40° (Ding et al., 2011; Ding et al., 2018a; Ding et al., 2020).

Constitutive Relation of Steel Tube

An elasto-plastic model, considering Von Mises yield criteria, Prandtl-Reuss flow rule and isotropic strain hardening, was used to describe the mechanical behaviors of steel. The expression for the stress-strain relationship of steel is shown in **Eq. 3** (Ding et al., 2011).

$$\sigma_i = \begin{cases} E_s\varepsilon_i & \varepsilon_i \le \varepsilon_y \\ f_y & \varepsilon_y < \varepsilon_i \le \varepsilon_{st} \\ f_y + \zeta E_s(\varepsilon_i - \varepsilon_{st}) & \varepsilon_{st} < \varepsilon_i \le \varepsilon_u \\ f_u & \varepsilon_i > \varepsilon_u \end{cases} \tag{3}$$

where σ_i is the equivalent stress and f_u equals to $1.5f_y$, which corresponds to the yield strength. E_s is taken as 2.06×10^5 MPa ε_i is the equivalent strain, while ε_y is the strain when steel yielded. ε_{st} is the hardening strain and equals to $12\varepsilon_y$. ε_u is the strain when the steel reaches ultimate strength and equals to $120\varepsilon_y$, and ζ equals to 1/216. The constitutive relation of steel tube exploited in this study is shown in the **Supplementary Figure S4**.

Model Validation

In this paper, the validity of established FE models of the RACFRST stub columns under axial compression was examined using the collected experimental results available in the literature (Shi et al., 2010; Yang and Hou, 2012; Ke et al., 2013; Chen M. C. et al., 2014; Chen X. X. et al., 2014; Huang et al., 2015; Dong et al., 2016; Xiang et al., 2016; Yang et al., 2020; Zhang et al., 2016; Wu et al., 2018). Due to the test method of mechanical properties on concrete adopted by various scholars and the compressive strength index used in design codes and formulae are different, the conversion formula of concrete cylinder strength f_c' to concrete cube strength f_{cu} (Chen et al., 1992) and the convention formula of 150 mm cube specimens ($f_{cu,150}$) to 100 mm cube specimens ($f_{cu,100}$) (Ding et al., 2011) were utilized.

$$f_c' = \begin{cases} 0.8f_{cu} & f_{cu} \le 50MPa \\ f_{cu} - 10 & f_{cu} > 50MPa \end{cases} \tag{4}$$

$$f_{cu,150} = 1.17f_{cu,100}^{0.95} - 0.7 \tag{5}$$

The comparison between FE analysis results and the test results of the collected RACFRST stub column specimens verified the feasibility and accuracy of established FE models. The ratio of test results to FE results ($N_{u,exp}/N_{u,FE}$) was presented in **Supplementary Table S1**. According to the normalized comparison, it was shown that the average value of the ratios ($N_{u,exp}/N_{u,FE}$) was 0.975, with the corresponding dispersion coefficient of 0.093, which indicates that the established FE model can precisely predict the axial bearing capacity of RACFRST columns. In the meantime, some typical load-strain curves of RACFRST stub columns obtained by FE analysis and test results were compared in **Supplementary Figure S5**. It can be seen that the ultimate bearing capacity and stiffness obtained from FE results and test results were in a good agreement. In particular, the curves before the peak load point obtained from the FE analysis coincides well with the test curves, while the FE curves after the peak load point of most of the specimens are slightly higher than the test curves. From the above comparisons, it could be found that good agreements were achieved between the FE and test results generally, especially for predicting ultimate capacity. Therefore, the established FE models could be employed to carry out the further parametric study of the RACFRST stub columns.

INVESTIGATION OF CONFINEMENT EFFECT AND EFFICIENCY OF RACFRST STUB COLUMNS UNDER AXIAL LOADING

Parameter Study

Based on the aforementioned validated FE modeling approach, a parametric study of 300 full-scale FE models is conducted to investigate the confinement effect and efficiency of RACFRST stub columns subjected to the axial loading. The parameters analyzed in this study are as follows: the width of rectangular cross-section D = 500mm; the length of rectangular cross-section $B = D$, $1.5D$, $2D$, $3D$ respectively; the columns length $L = 3B$; the cross-sectional steel ratio ρ = 0.02, 0.05, 0.08 respectively. $f_{cu,0}$ represents the cubic compressive strength of the infilled concrete with the recycled aggregate replacement ratio is 0%. The concrete strength is $f_{cu,\,0}$ = 30 MPa, 50 MPa paired with steel strength f_y = 235 MPa, $f_{cu,\,0}$ = 50 MPa, 70 MPa paired with f_y = 345 MPa, and $f_{cu,\,0}$ = 70 MPa paired with f_y = 420 MPa, the replacement ratio of recycled aggregate r = 0, 25, 50, 75, 100%, as shown in **Supplementary Table S2**. The influence of the concrete strength, steel strength, steel ratio, and the replacement ratio of recycled aggregate on the axially loaded behaviors were presented in **Supplementary Figure S6** in the form of the typical N-ε_L curves. Similar to the CFRST stub columns under axial compression, the concrete strength, steel strength, and steel ratio significantly influence the ultimate bearing capacity of RACFRST stub columns at different replacement ratios of recycled aggregate.

Evaluation Criterion of the Confinement Effect and Efficiency

The confinement effect of steel tube on the filled concrete can be assessed by the radial concrete stress of confined area $\sigma_{r,c.}$ The confinement efficiency of steel tube on the infilled concrete can evaluated by the radial concrete confinement coefficient [$\xi_{r,c} = \sigma_{r,c}/(\rho f_y)$] and the intersection time of axial stress-strain curve and transverse stress-strain curve. The greater the radial concrete confinement coefficient, the stronger the steel tube's confinement efficiency on the infilled concrete. When the RACFRST was concentrically loaded, the infilled concrete and the steel tube were compressed together until the axial yield stress was reached. Then the steel tube began to play a confinement role when the infilled concrete expanded increasingly, and the transverse stress of the steel tube became larger. The steel stress-strain curves could reflect the composite action and the intersection of the axial stress-strain curve and the transverse stress-strain curve represents the best composite action point of the composite structures. The earlier the intersection of the axial stress-strain curve and the transverse stress-strain curve occurred, the better the composite action and the confinement efficiency were (Ding et al., 2018b). Hence, the indexes mentioned above were utilized herein to evaluate the confinement effect and efficiency as the design parameters change. It is worth mentioning that the previous studies have concluded that the confinement effect of the outer steel tube on the infilled concrete of concrete-filled rectangular steel tubular (CFRST) stub column is mainly concentrated at the corners (Ding et al., 2018a). The corner point data in the middle section is extracted from the FE models to emphasize the impact of the recycled aggregate replacement ratio in the following parameter analysis.

Concrete Strength

The influence of concrete strength ($f_{\mathrm{cu},\,0}$) on the confinement effect and efficiency of RACFSST stub columns is shown in **Supplementary Figure S7**. As shown in the figure, the radial stress $\sigma_{r,\mathrm{c}}$ and the radial concrete confinement coefficient $\xi_{r,\mathrm{c}}$ of $f_{\mathrm{cu},\,0} = 70$ MPa group are slightly lower in the early stage but are more significant in the late stage of the loading process. Meanwhile, the intersection of the axial stress-strain curve and the transverse stress-strain curve of $f_{\mathrm{cu},0} = 70$ MPa group occurred earlier. A conclusion can be drawn here that with the increment of concrete strength, the RACFSST columns subjected to axial loading has a slightly higher confinement effect and efficiency on the infilled concrete.

Steel Strength

The influence of steel strength (f_{y}) on the confinement effect of RACFSST stub columns is shown in **Supplementary Figure S8A**. The radial stress $\sigma_{r,\mathrm{c}}$ of $f_{\mathrm{y}} = 235$ MPa group is lower than that of $f_{\mathrm{y}} =$ 345 MPa group, indicating that the RACFSST columns have a higher confinement effect with the increase of steel strength. However, the radial concrete confinement coefficient $\xi_{r,\mathrm{c}}$ of $f_{\mathrm{y}} = 235$ MPa group is higher than that of $f_{\mathrm{y}} = 345$ MPa group in **Supplementary Figure S8B**, and the intersection of the axial stress-strain curve and the transverse stress-strain curve of $f_{\mathrm{y}} = 235$ MPa group is earlier compared with that of $f_{\mathrm{y}} = 345$ MPa group in **Supplementary Figure S8C**. Thus, with the increment of steel strength, the outer steel tube has a weaker confinement efficiency on the infilled concrete.

Cross-Sectional Steel Ratio

The influence of steel ratio (ρ) on the confinement effect and efficiency of RACFSST stub columns is shown in **Supplementary Figure S9**. From **Suplementary Figure S9A**, the outer steel tube has a higher confinement effect on the infilled concrete with the increment of steel ratio. From the **Supplementary Figures S9B,C**, with the increment of steel ratio, the radial concrete confinement coefficient $\xi_{r,\mathrm{c}}$ becomes lower, and the intersection of the axial stress-strain curve and the transverse stress-strain curve is delayed, which indicate the decrease of confinement efficiency. From the above discussion, the steel tube with higher steel ratio has a weaker confinement efficiency on the infilled concrete.

The Replacement Ratio of Recycled Aggregate

Suplementary Figures S7–S9 present the FE results of RACFSST stub columns with the different replacement ratio of recycled aggregate. According to the comparison made, following mechanical behaviors of RACFSST stub columns can be observed:

1. As the replacement ratio of recycled aggregate increases, the radial stress of infilled concrete and the radial concrete confinement coefficient $\xi_{r,\mathrm{c}}$ of RACFSST stub columns are smaller at the early stage of the loading process. However, the radial stress of infilled concrete and the radial concrete confinement coefficient $\xi_{r,\mathrm{c}}$ of RACFSST stub columns with different recycled aggregate replacement ratio tend to be the same at the late stage.
2. As the replacement ratio of recycled aggregate increases, the elastic modulus and uniaxial compressive strength of recycled aggregate concrete decrease which is the major factor of the reduction of ultimate bearing capacity and the intersection point of the axial stress-strain curve and transverse stress curve is slightly postponed.

The above observations indicate that the replacement ratio of recycled aggregate has a little effect on the confinement effect and efficiency of the outer steel tube on the infilled concrete compared with other design parameters investigated in this parametric study.

The Aspect Ratio of the Cross-Section

The influence of aspect ratio of cross-section on the confinement effect and efficiency of RACFRST stub columns is shown in **Supplementary Figure S10**. From the **Supplementary Figures S10B,C**, with the increment of aspect ratio, the radial stress of infilled concrete becomes lower, and the intersection of the axial stress-strain curve and the transverse stress-strain curve is delayed, which show the decrease of confinement effect and efficiency.

Comparison of CFRST and RACFRST Stub Columns Under Axial Compression

Based on the parametric FE analysis of RACFRST stub columns, the infilled concrete stress nephogram at mid-height cross-section for CFRST and RACFRST stub columns with the same parameters ($D = B = 500$ mm, $L = 1{,}500$ mm, $\rho = 0.05$, $f_{\mathrm{y}} = 345$ MPa, $f_{\mathrm{cu},0} = 50$ MPa) were extracted as shown in **Supplementary Figure S11**. The comparison shows that the steel tube has a confinement effect on infilled NC and infilled RAC. The confinement effect of the steel tube is slightly weaker in RACFRST stub columns with the increase of replacement ratio of recycled aggregate, but the difference is not obvious. The confinement area of RACFRST stub columns is based on the infilled concrete stress nephogram at mid-height cross-section at ultimate bearing capacity. The infilled concrete stress nephogram at mid-height cross-section of RACFRST stub columns with the different aspect ratios ($D = 500$ mm, $\rho = 0.05$, $r = 50\%$, $f_{\mathrm{y}} = 345$ MPa, $f_{\mathrm{cu},0} = 50$ MPa) are shown in **Supplementary Figure S12**. The dark area is that the axial stress of the infilled concrete of RACFRST stub columns is less than or equal to the average axial stress of the same size concrete. The average ratio of the non-confinement area $A_{\mathrm{c}1}$ and the confinement area $A_{\mathrm{c}2}$ to the overall area of the infilled concrete A_{c} is shown in **Supplementary Table S3**.

retically evaluate the confinement effect and efficiency of composite columns, a simplified diagram was applied herein which lay the foundation of the following derivation of the theoretical equation. When the infilled concrete reached the ultimate limit state, the model simplification completely conforms with the stress distribution and the superposition theory. Where A_c is the cross-sectional area of the infilled concrete. A_s is the cross-sectional area of the steel tube. B and D are the length and width of the steel tube, respectively, t is the wall thickness of the steel tube, as shown in **Supplementary Figure S13**. The following relationships could be expressed as:

$$\begin{cases} A_c = (B-2t)(D-2t) \\ A_s = BD - (B-2t)(D-2t) \end{cases} \tag{6}$$

$$\rho = \frac{BD - (B-2t)(D-2t)}{BD} \tag{7}$$

PRACTICAL DESIGN FORMULA OF THE LOAD-BEARING CAPACITY OF RACFRST STUB COLUMNS

Formulation

For RACFRST stub columns, the following expressions were presented, where f_y is the yield strength of steel, $\sigma_{L,s}$ is compressive stress of steel tube, $\sigma_{\theta,s}$ is transverse tensile stress of steel tube, $\sigma_{r,c}$ is radial concrete stress of confined area, $\sigma_{L,c}$ is axial compressive stress of infilled concrete. The relationship between $\sigma_{r,c}$ and $\sigma_{\theta,s}$ in the inelastic stage can be expressed as (Ding et al., 2018a):

$$\begin{cases} \sigma_{r,c1} = \dfrac{2\sigma_{\theta,s1}}{D/t-2} \\ \sigma_{r,c2} = \dfrac{2\sigma_{\theta,s2}}{B/t-2} \end{cases} \tag{8}$$

when RACFRST stub columns reach the ultimate strength ($f_{sc} = N_u/A_{sc}$, $A_{sc} = A_c + A_s$), the average ratio of axial compressive stress ($\sigma_{L,s}$) and transverse tensile stress ($\sigma_{\theta,s}$) of steel tube are shown in **Supplementary Figures S14, S15** and **Supplementary Table S3**, and the average of A_{c1}/A_c and A_{c2}/A_c is shown in **Supplementary Table S3**.

$$A_{s1} = \alpha A_s, A_{s2} = \beta A_s, A_{c1} = \chi A_c, A_{c2} = \delta A_c \tag{9}$$

$$\sigma_{\theta,s1} = af_y, \sigma_{\theta,s2} = bf_y, \sigma_{L,s1} = cf_y, \sigma_{L,s2} = df_y \tag{10}$$

The axial compressive stress ($\sigma_{L,c}$) of constrained infilled concrete could be given as:

$$\sigma_{L,c} = f_c + k_1\sigma_{r,c} = f_c + k_1\left(\frac{t\sigma_{\theta,s1}}{D-2t} + \frac{t\sigma_{\theta,s2}}{B-2t}\right) \tag{11}$$

$$\sigma_{r,c} = \frac{\sigma_{r,c1} + \sigma_{r,c2}}{2} = \frac{t\sigma_{\theta,s1}}{D-2t} + \frac{t\sigma_{\theta,s2}}{B-2t} \tag{12}$$

where k_1 is the coefficient of lateral pressure, $k_1 = 3.4$, according to Ding et al. (Ding et al., 2011).

According to the static equilibrium method, the ultimate bearing capacity N_u of RACFRST stub columns under axial loading could be expressed as:

$$\begin{aligned} N_u &= f_cA_{c1} + \sigma_{L,c}A_{c2} + \sigma_{L,s1}A_{s1} + \sigma_{L,s2}A_{s2} \\ &= f_cA_{c1} + \left[f_c + k_1\left(\frac{t\sigma_{\theta,s1}}{D-2t} + \frac{t\sigma_{\theta,s2}}{B-2t}\right)\right]A_{c2} + \sigma_{L,s1}A_{s1} + \sigma_{L,s2}A_{s2} \\ &= f_cA_{c1} + f_cA_{c2} + k_1\left(\frac{t\sigma_{\theta,s1}}{D-2t} + \frac{t\sigma_{\theta,s2}}{B-2t}\right)\delta(B-2t)(D-2t) + c\alpha f_yA_s + d\beta f_yA_s \\ &= f_cA_c + k_1\delta\left[t\sigma_{\theta,s1}(B-2t) + t\sigma_{\theta,s2}(D-2t)\right] + (c\alpha + d\beta)f_yA_s \\ &= f_cA_c + k_1\delta\left[Bt\sigma_{\theta,s1} + Dt\sigma_{\theta,s2} - 2t^2(\sigma_{\theta,s1} + \sigma_{\theta,s2})\right] + (c\alpha + d\beta)f_yA_s \end{aligned} \tag{13}$$

Since t^2 is infinitesimal and can be ignored, N_u can be simplified to:

$$\begin{aligned} N_u &= f_cA_c + k_1\delta\left(Bt\sigma_{\theta,s1} + Dt\sigma_{\theta,s2}\right) + (c\alpha + d\beta)f_yA_s \\ &= f_cA_c + \frac{k_1\delta\left(A_{s2}\sigma_{\theta,s1} + A_{s1}\sigma_{\theta,s2}\right)}{2} + (c\alpha + d\beta)f_yA_s \\ &= f_cA_c + \left[\frac{k_1\delta(a\beta + b\alpha)}{2} + c\alpha + d\beta\right]f_yA_s \end{aligned} \tag{14}$$

N_u could be obtained as:

$$N_u = f_cA_c + Kf_yA_s \tag{15}$$

The confinement coefficient K obtained from **Eq. 15** is closed to the confinement coefficient K of CFRST stub columns (Ding et al., 2018a), and the difference is less than 1%, so unified $K = 1.04 - 0.06\ln(B/D - 0.9)$ (Ding et al., 2018a), which shows there is not much difference between the confinement effect of RACFRST stub columns and the confinement effect of CFRST stub columns when subjected to axial load.

Formula Validation

The ultimate bearing capacity under axial loading calculated from **Eq. 15** (N_u), test results ($N_{u,exp}$) and FE results ($N_{u,FE}$) for RACFRST stub columns were compared, as shown in **Supplementary Figure S16** and **Supplementary Table S1**. **Supplementary Figures S16A–C** show that the ultimate bearing capacity calculated by the proposed equation is in a good agreement with that of $N_{u,exp}$ and $N_{u,FE}$. The average ratio of $N_{u,exp}$ to $N_{u,FE}$, $N_{u,exp}$ to N_u and $N_{u,FE}$ to N_u is 0.975, 1.005,1.036 with the corresponding dispersion coefficient is 0.093, 0.089, 0.094, respectively. As a result, the proposed equation gives an accurate estimation of ultimate axial bearing capacity of RACFRST stub columns.

Comparison of Formulae

To fully explain the advantages of the proposed equation, comparison with some current design codes and well-known design formulae were conducted. The range of applicability of design equations were shown in **Supplementary Table S4**. Firstly, shown in **Supplementary Figure S17** and **Supplementary Table S5**, the experimental results were compared with design codes (BS EN 1994-1-1, 2004; ANSI/AISC 360-16, 2016; T/CECS-625-2019, 2019) and **Eq. 15**, and the same data are used in the comparison. "Total" represents the sum of the specimens participating in the formulae calculation due to the scope limitation of formulae' application. The average ratio of $N_{u,exp}$ to $N_{u,\ T/CECS\text{-}625(2019)}$, $N_{u,\ EC4(2004)}$ and $N_{u,\ AISC\ 360\text{-}16(2016)}$ is 1.051, 1.111 and 1.136 and the corresponding $N_{u,exp}$ to N_u is 1.054, 1.040 and 1.010, respectively.

The dispersion coefficient of $N_{u,exp}$ to $N_{u,\ T/CECS\text{-}625(2019)}$, $N_{u,\ EC4(2004)}$ and $N_{u,\ AISC\ 360\text{-}16(2016)}$ is 0.052, 0.071 and 0.086 and the corresponding $N_{u,exp}$ to N_u is 0.058, 0.073 and 0.085, respectively. The accuracy of $N_{u,exp}$ to $N_{u,\ T/CECS\text{-}625(2019)}$ is slightly higher than that of $N_{u,exp}$ to N_u, the application range of T/CECS-625-2019 (2019) code is not as wide as **Eq. 15**, and the prediction errors between T/CECS-625-2019 (2019) code and **Eq. 15** is less than 1%. Therefore, the proposed formula (**Eq. 15**) has higher accuracy compared with the current design codes.

Then as shown in **Supplementary Figure S18** and **Supplementary Table S6**, the experimental results were compared with design formulas proposed by other scholars (Chen et al., 2013; Niu and Cao, 2015; Zhang et al., 2016) and **Eq. 15** and the same data are used in the comparison. The average ratio of $N_{u,exp}$ to $N_{u,\ Zhang}$, $N_{u,\ Chen}$ and $N_{u,\ Niu}$ is 1.037, 0.980 and 1.065 with the corresponding dispersion coefficient is 0.096, 0.080 and 0.083, respectively. The average ratio of $N_{u,exp}$ to N_u is 1.004 with the corresponding dispersion coefficient is 0.089. Therefore, compared with the well-known design formula, the proposed formula (**Eq. 15**) has higher accuracy and simpler calculation, and the difference in the dispersion of the result of the formula is tiny. In general, the proposed equation is more accurate and concise than current design formulae in codes and available literature. Meanwhile, the derivation of the proposed equation reflects the confinement effects of the composite columns on their ultimate bearing capacity.

CONCLUSION

In this study, parametric studies are conducted through the FE models validated by experimental results to investigate the confinement coefficient of recycled aggregate concrete-filled rectangular steel tubular (RACFRST) stub columns under axial loading. Furthermore, the confinement effect and efficiency between the steel tube and infilled RAC were compared with that of NC counterparts. A practical and straightforward formula is proposed to predict the ultimate bearing capacity of RACFRST stub columns and the precision and practicability of the proposed formula were verified to be well satisfied compared with tested results and FE results. To sum up, the following conclusions could be drawn:

1. Based on triaxial plastic-damage RAC constitutive relations and steel constitutive model adopted in this paper, FE models of RACFRST stub columns subjected to the axial compression can be reasonably established. The FE results were in a good agreement with the test results, which indicates the FE modeling approach was valid and feasible.
2. On the basis of a validated FE modeling method, parameter study was performed on the full-scale RACFRST stub columns. The radial concrete stress of confined area $\sigma_{r,c}$ reflect the confinement effect of steel tube on the infilled concrete. The radial concrete confinement coefficient [$\xi_{r,c} = \sigma_{r,c}/(\rho f_y)$] and the intersection time of axial stress-strain curve and transverse stress-strain curve reflect the confinement efficiency of steel tube on the infilled concrete. The analytical results indicate that the confinement effect and efficiency between the steel tube and infilled RAC was slightly weaker than that of normal concrete counterparts.
3. According to the parametric analysis, the radial stress–axial strain curves indicate that the concrete strength, steel strength, steel ratio and aspect ratio have a significant impact on the confinement effect under axial loading. However, as the replacement ratio of recycled aggregate increases, the ultimate bearing capacity of RACFRST stub columns is slightly decreased due to the reduction of elastic modulus and uniaxial compressive strength of recycled aggregate concrete. The replacement ratio of recycled aggregate has a minor effect on the confinement effect and efficiency of the steel tube on the infilled concrete at the ultimate bearing capacity.
4. The formula of the ultimate bearing capacity of RACFRST stub columns was proposed based on the superposition method. In the expression, the confinement coefficient of RACFRST stub columns was $K = 1.04–0.06\ln(B/D\text{-}0.9)$, which was same as the confinement coefficient of CFRST stub columns. The proposed equation is more accurate and concise than current design formulae in codes and available literature and can clearly explain the confinement effect and efficiency of the steel tube on the infilled RAC at the ultimate state.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

YL: Investigation, Formal analysis, Writing—Original draft preparation, Visualization. FL: Writing—Original Draft, Writing—Review and Editing, Visualization. FD: Conceptualization, Methodology, Supervision. EW: Investigation, Formal analysis. YX: Investigation, Formal analysis CD: Formal analysis. TY: Formal analysis. CL: Investigation.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmats.2021.630774/full#supplementary-material.

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The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.