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Analytical Modelling of LACFCST Stub Columns Subjected to Axial Compression

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Abstract: This paper presents a numerical investigation of lightweight aggregate concrete-filled circular steel tubular (LACFCST) stub columns under axial compression. A finite 3D solid element model of the LACFCST stub column was established by adopting a plastic-damage constitutive model of lightweight aggregate concrete (LAC). The finite element model (FEM) analysis results revealed that the confinement effect of the steel tube on the infilled LAC was weaker than that on the infilled conventional concrete. A parametric study making use of 95 full-scale FEMs was conducted to investigate the influences of various design parameters of LACFCST stub columns on their ultimate axial bearing capacity and the composite actions. Moreover, a numerical model of the axial and transverse stress of steel tubes at the ultimate state of LACFCST columns was proposed using the regression method. Based on the equilibrium conditions and the proposed model, a practical design formula making use of an enhancement factor was derived to estimate the ultimate bearing capacity of LACFCST stub columns by using the superposition method. The validity of the proposed formula was verified against the experimental data of 49 LACFCST stub column specimens under the axial loading available in the literature. Meanwhile, the accuracy and conciseness of the proposed formula were evaluated by comparison with the formulas suggested by the existing design codes.

Keywords: concrete-filled circular steel tube; LAC; finite element analysis; ultimate bearing capacity; confinement coefficient

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1. Introduction

In the past several decades, steel–concrete composite structures have been increasingly used in long-span bridges and super high-rise buildings around the world with the progress of social demands. A tendency to ascend the scale of engineering structures caused the self-weight of structural members to become a crucial factor in design, affecting the construction difficulty and the cost. T. G. Ghazijahani et al. [1] modified composite columns using timber as the infilled material, aiming to reduce the self-weight. With the merits of being lightweight and high-strength with good seismic performance, LAC is considered one of the effective ways to reduce structural dead load among the engineering community. Compared with conventional concrete which uses natural aggregates, the unit mass of LAC with a similar strength level is 20–30% lighter, yet its mechanical performance, such as the ductility [2] and bond strength [3], may be even better in some cases. These superior behaviors of LAC give it broad application prospects, especially in the aforementioned large-scale structures. On the other hand, LAC is more prone to aggregate fracture, which leads to lower elastic modulus and increased brittleness compared with conventional concrete. These defects have been experimentally verified by existing studies [4], and the importance of providing rational confinement in the usage of LAC has been noticed. Currently, concrete-filled steel tube (CFST) columns are one of the most favored and versatile composite members in structural engineering and are extensively utilized as

bridge piers and building columns, and utilized in elevated structures. The composite action, namely the interaction between the steel tube and infilled concrete, enables the columns to fully exploit the advantages of constituent materials and circumvent their defects. Therefore, the CFST columns show an upgraded mechanical performance in their load-carrying capacity, ductility and energy dissipation capacity [5–7] compared to conventional structural columns, such as reinforced concrete and hollow steel columns. Since the outer steel tube can serve as a significant reinforcement of infilled concrete, infilling the LAC into the steel tube, forming a type of composite structural column, is thereby expected to have a satisfactory improvement of the mechanical performance of LAC.

The lightweight aggregate concrete-filled steel tubular columns have already gained some interest among the academic society. Ghannam et al. [8] conducted a series of tests of the square, rectangular and circular steel tubes filled with conventional concrete and LAC to investigate the failure modes of the composite columns. The test results revealed that both types of the composite columns lose their bearing capacity due to the overall buckling of the outer steel tubes; M. Abhilash et al. [9] presented an experimental investigation of CFST columns using semi-lightweight aggregate concrete as an infill, and investigated the effects of variations in the diameter, width, thickness and length-to-diameter ratio of the outer steel tube on the ultimate axial load-bearing capacity and axial shortening behaviors of both the circular and square columns. Based on the experimental investigations, the semi-lightweight aggregate concrete can serve as an alternative to the conventional concrete in CFST columns. The strength behaviors of semi-lightweight concrete were enhanced by the confinement of the steel tube. Thus, it provides comparable axial load-carrying capacity with a smaller self-weight. Salgar et al. [10] conducted an experimental and analytical study on the lightweight aggregate concrete-filled steel tubular columns with the cross-section types of circular, square and rectangular, subjected to the concentric load to failure. The ultimate strength obtained from the test was compared to the current specifications governing the design of CFST stub columns, such as Eurocode 4 [11] and American standards [12]. The results suggested that the load-carrying capacity of lightweight aggregate concrete-filled steel tubular columns were found to be comparable to conventional concrete-filled specimens, and the circular tubes can provide substantial post-yield strength and stiffness, while the square and rectangular cross-sections cannot. Zhang et al. [13] investigated the axial compressive performance of LACFCST stub columns with different replacement ratios of normal gravel aggregate, and the results revealed that the ultimate bearing capacities and the corresponding displacements of the stub columns increased with an increase in the normal gravel replacement ratio. Fu et al. [14–17] conducted experiments on LACFCST stub columns for the interface bond behaviors between the steel tube and infilled LAC, and a calculation method for ultimate bearing capacity was proposed. Gao and Li [18] performed an experimental study on the seismic behaviors of a lightweight aggregate concrete-filled rectangular steel tubular (LACFRST) frame. In their study, by testing four specimens subjected to a constant axial load and horizontal cyclic load, the LACFRST frame was verified to have excellent seismic behaviors compared to the specimens filled with standard weight concrete.

To sum up, the mechanical behaviors of lightweight aggregate concrete-filled steel tubular columns have been experimentally investigated in past research. However, there is still a lack of the theoretical basis and numerical analysis of the composite actions of LACFCST stub columns under an axial load. Due to the limitation of measuring technology, a detailed FEM analysis is the only method capable of investigating the interaction between the components of CFST columns during the loading process. Different from the existing studies about the CFST columns, which has a large number of advanced numerical analyses, a rare FEM analysis of LACFCST has been performed. Meanwhile, the difference between the confinement effectiveness of LACFCST and concrete-filled circular steel tubular (CFCST) stub columns also need to be clearly illustrated so that the current design formulas of CFCST columns can be rationally modified.

Therefore, the objective of the presented study is to investigate the composite action in LACFCST columns numerically and to propose a numerical model and design formula based on our past research of CFCST stub columns [19,20]. The main contents of this paper include the following: (1) a fine-meshed finite 3D solid element model of LACFCST stub columns was established by adopting an elastoplastic constitutive model of steel and a plastic-damage constitutive model of LAC. The non-linear finite element (FE) analysis was carried out, and the validity of the presented numerical analysis was verified against the collected experiment results of the ultimate bearing capacity and the whole loading-shortening curves; (2) based on the validated model, a parametric study was performed, and the different composite action between the LACFCST and CFCST stub columns was discussed. A composite action model of LACFCST stub columns was proposed; (3) based on the composite action model, a practical design formula utilizing an enhancement factor was proposed to predict the ultimate bearing capacity of the LACFCST stub columns. The proposed design formula was evaluated by comparison of the existing formulas in current design codes using available experimental data.

2. Finite Element Modelling of LACFCST Stub Columns

2.1. Constitutive Relation of the Steel Tube

An elastoplastic model incorporating the von Mises yield criteria, Prandtl–Reuss flow rule and isotropic strain hardening rule was used to describe the constitutive behaviors of the outer steel tube and loading plate. The expression of the constitutive stress–strain relationship of steel is described as follows [21]:

$$\sigma_i = \begin{cases} E_s \varepsilon_i & \varepsilon_i \leq \varepsilon_y \\ f_y & \varepsilon_y \leq \varepsilon_i \leq \varepsilon_{st} \\ f_y + \zeta E_s (\varepsilon_i - \varepsilon_{st}) & \varepsilon_{st} \leq \varepsilon_i \leq \varepsilon_u \\ f_u & \varepsilon_i > \varepsilon_u \end{cases} \quad (1)$$

where σ_i and ε_i are the equivalent stress and strain of steel. f_y and $f_u = 1.5f_y$ are the yield strength and ultimate strength of steel, respectively. $E_s = 2.06 \times 10^5$ MPa is the elastic modulus of steel. ε_y , ε_{st} , ε_u are the yield strain, hardening strain and ultimate strain of steel, respectively, where ε_{st} is defined as $12 \varepsilon_y$ and ε_u is taken as $120 \varepsilon_y$. The hardening parameter ζ is taken as $1/216$. The detailed stress–strain curves are shown in Figure 1a.

Figure 1. Stress–strain curves of steel tube and LAC: (a) steel tube; (b) LAC.

2.2. Constitutive Relation of Lightweight Aggregate Concrete

A uniaxial constitutive model of LAC which is suitable for different LAC strengths, proposed by Ding et al. [22], was adopted for the simulation of infilled LAC in the presented study:

$$y = \begin{cases} \frac{Ax + (B-1)x^2}{1 + (A-2)x + Bx^2} & x \leq 1 \\ \frac{x}{\alpha(x-1)^2 + x} & x > 1 \end{cases} \quad (2)$$

where $y = \sigma/f_c$ and $x = \varepsilon/\varepsilon_c$ are the stress and strain ratios of LAC, respectively. σ and ε are the stress and strain of the infilled LAC. $f_c = 0.88 f_{cu}$ is the uniaxial compressive strength of LAC, where f_{cu} is the compressive cubic strength of LAC. ε_c is the strain corresponding with the peak compressive stress of LAC, where $\varepsilon_c = 730 f_{cu}^{1/3} \times 10^{-6}$. The parameter A is the ratio of the initial tangent modulus to the secant modulus at peak stress and equals to $1.68 \times 10^{-3} \rho_c f_{cu}^{-1/6}$, where ρ_c is the bulk density of LAC. $B = 5(A - 1)^2/3$ is a parameter that controls the decrease in the elastic modulus along the ascending branch of the axial stress–strain relationship. The stress–strain curves of LAC under uniaxial compression for several strength grades are shown in Figure 1b. For a LACFCST stub column, parameter α can be taken as 0.15. More detailed information of the LAC constitutive model under a tension state could be referred to in reference [22].

2.3. Element Type and Mesh Size

The FEMs of LACFCST stub column were established using the ABAQUS, version 6.14-4 [23]. In the FEMs, the 8-node reduced integral format 3D solid element (C3D8R) had three translational degrees of freedom per node, and was applied to simulate the steel tube, infilled LAC and loading plate [24]. The structured meshing technique in ABAQUS was adopted in this study, and the mesh size was approximately 50 mm, according to the dimensions of collected test specimens for the efficiency and accuracy. The typical mesh of the steel tube, infilled LAC and load plate are shown in Figure 2a,c, while the entire model of LACFCST columns is shown in Figure 2d.

Figure 2. Mesh of the FEMs: (a) steel tube; (b) core concrete; (c) loading plate; (d) whole model.

2.4. Contact Interaction, Boundary Conditions and Loading

A “surface-to-surface” contact model was adopted for the simulation of interactions between the steel tube and infilled LAC/standard weight concrete (hereinafter referred to as infilled concrete), in which the inner surface of steel tube was selected as the master surface, and the external surface of the concrete was chosen as the slave surface. The limited slip was used in the sliding formulation, and the discretization method was “surface-to-surface”. Tangential behavior and normal behavior were defined as the contact property to simulate the interfacial bond–slip relationship between the steel tube and infilled concrete. The penalty function was utilized in the friction formula for the tangential behavior in which the friction coefficient was 0.5 [21,25], and the normal behavior was set to “hard” contact which allows separation after contact occurs. In ABAQUS, the tie connection can

couple two separate surfaces so that no relative motion occurs between them; hence, the tie connection was adopted to connect the upper surface of the steel tube and infilled concrete to the bottom surface of the loading plate so that the axial load could be uniformly and simultaneously applied to the whole cross-section. The bottom surface of the loading plate was selected as the master surface while the top surface of the steel tube and infilled concrete was the slave surface.

The boundary condition of the column model is as follows: both ends of the stub column were fixed against all degrees of freedom except for the vertical displacement at the top end, as shown in Figure 3. The loading was applied in the manner of displacement control at the top center of the loading plate with a thickness of 20 mm.

Figure 3. Boundary conditions of the FEMs.

2.5. Constitutive Model Parameter Settings

The tri-axial plastic-damage behaviors of the LAC in composite columns were defined in the Concrete Damaged Plasticity (CDP) model available in ABAQUS. The Poisson's ratio of the LAC in the elastic stage is taken as 0.2; the eccentricity is 0.1; the ratio of the initial equibiaxial compressive yield stress to the initial uniaxial compressive yield stress (f_{b0}/f_{c0}) is 1.16; the ratio of the second stress invariant on the tensile meridian to that on the compressive meridian is 2/3; the viscosity parameter is 0.0005.

The dilation angle is a parameter that needs to be defined in the CDP model and has an evident impact on the simulated mechanical behaviors of infilled concrete in the composite columns [26]. In the existing numerical studies of CFST columns, the dilation angle of around 40° was the most selected [21]. However, this value may lead to inaccurate modeling of LACFCST columns due to the different confinement effect. Therefore, an investigation was performed to determine a rational value of LAC's dilation angle by searching for the FE analysis results that best fit the test results. FE analyses on 49 specimens in references [14,15,27] with the dilation angles of 30° , 35° , and 40° , respectively, were carried out. The ultimate bearing capacities obtained from the FEMs analyses ($N_{u,FE}$) and test results ($N_{u,Exp}$) are shown in Figure 4 and Table 1. It can be seen that the average values of the ratios ($N_{u,Exp}/N_{u,FE}$) with the dilation angles of 30° , 35° , and 40° are 0.997, 0.947, and 0.923 with a coefficient of variation (C.V.) of 0.034, 0.042, and 0.045, respectively. In particular, the maximum deviation in these specimens is SC12-a, which has an ultimate bearing capacity of 721 kN in the experiment, and 790 kN, 871 kN, and 899 kN with the dilation angles of 30° , 35° , and 40° respectively. When the dilation angles were 30° , 35° , and 40° , the percentages of deviation were 9.6%, 20.8%, and 24.7% respectively. The comparison results indicated that the dilation angle of 30° best fit the test results of LACFCST stub columns.

Table 1. Comparison of average ratio with different dilation angle.

Dilation Angle	30°	35°	40°
Average ratio ($N_{u,Exp}/N_{u,FE}$)	0.997	0.947	0.923
C.V.	0.034	0.042	0.045

Figure 4. The ultimate bearing capacities obtained from tests and FEMs with different dilation angles.

2.6. Geometric Imperfection and Residual Stresses

Geometric imperfection is divided into overall geometric imperfection and local geometric imperfection. The geometric imperfection effect of the steel tube was considered in the FEMs of the LACFCST stub column under axial compression. When the first and fifteenth modes were obtained through the eigenvalue buckling analysis, these two modes were respectively introduced as the overall initial geometric imperfection and the local initial geometric imperfection of FEMs. Based on this kind of state, the non-linear FE analysis was run to obtain the ultimate compressive failure.

Residual stresses are generally present in the steel tube of the LACFCST stub column due to forming and welding. M. Ashraf et al. [28] and L. Gardner et al. [29] proved that the initial stiffness will be decreased slightly because of the residual stress in the steel tube, and it has little effect on the overall performance of the columns. Furthermore, the effect of residual stress will be further insignificant when working with the infilled concrete [30,31]. Therefore, the FEMs of LACFCST stub columns were established without considering the effect of residual stresses on the performance of the columns.

3. Finite Element Analysis

3.1. Model Validation

A total of 49 tested results from references [14,15,27] of LACFCST stub columns were collected. Correspondingly, a fine-meshed FEM analysis of the LACFCST stub columns under axial compression was performed for each specimen. The validity of the established models was verified against the experimental results. The ultimate bearing capacity of FE results was compared with the experimental results, and the ratio of test results to FE results ($N_{u,Exp}/N_{u,FE}$) are presented in Table 2. It was shown that the average value of the ratios ($N_{u,Exp}/N_{u,FE}$) is 0.997 with the corresponding C.V. of 0.034. It indicated that the ultimate bearing capacity obtained from the FE results and test results are in good agreement.

Table 2. Specimen details and comparisons of load-bearing capacities obtained from FEM and Exp.

Specimens	Ref.	$D \times t \times L$ (mm)	E_c (MPa)	f_c (MPa)	f_y (MPa)	$N_{u,Exp}$ (kN)	$N_{u,FE}$ (kN)	$N_{u,Exp}/N_{u,FE}$
SC1-a	[14]	$111.2 \times 2.04 \times 342$	23,840	29.21	305.6	659	651	1.013
SC1-c		$111.5 \times 2.11 \times 342$	23,840	29.21	305.6	675	661	1.021
SC2-a		$111.4 \times 2.06 \times 342$	24,830	37.66	305.6	738	752	0.982
SC2-b		$111.4 \times 2.19 \times 342$	24,830	37.66	305.6	689	729	0.945
SC2-c		$111.3 \times 2.12 \times 342$	24,830	37.66	305.6	678	708	0.957
SC3-a		$113.5 \times 3.79 \times 342$	23,840	29.21	274.7	852	821	1.038
SC3-b		$113.4 \times 3.78 \times 342$	23,840	29.21	274.7	822	804	1.023
SC4-a		$113.3 \times 3.79 \times 342$	24,830	37.66	274.7	884	909	0.972
SC4-b		$113.4 \times 3.81 \times 342$	24,830	37.66	274.7	889	920	0.966
SC4-c		$113.3 \times 3.75 \times 342$	24,830	37.66	274.7	899	942	0.954
SC5-b		$164.5 \times 2.64 \times 495$	23,840	29.21	281.7	1214	1192	1.018
SC5-c		$164.4 \times 2.51 \times 495$	23,840	29.21	281.7	1403	1315	1.067
SC6-a		$164.3 \times 2.63 \times 495$	24,830	37.66	281.7	1475	1503	0.981
SC6-c		$164.8 \times 2.45 \times 495$	24,830	37.66	281.7	1540	1486	1.036
SC7-a		$165.5 \times 2.99 \times 495$	23,840	29.21	293.9	1410	1360	1.037

Table 2. Cont.

Specimens	Ref.	$D \times t \times L$ (mm)	E_c (MPa)	f_c (MPa)	f_y (MPa)	$N_{u,Exp}$ (kN)	$N_{u,FE}$ (kN)	$N_{u,Exp}/N_{u,FE}$
SC7-b		$165.2 \times 3.01 \times 495$	23,840	29.21	293.9	1340	1421	0.943
SC7-c		$165.2 \times 3.11 \times 495$	23,840	29.21	293.9	1547	1466	1.055
SC8-b		$164.5 \times 3.11 \times 495$	24,830	37.66	293.9	1647	1626	1.013
SC8-c		$165.0 \times 2.96 \times 495$	24,830	37.66	293.9	1629	1689	0.964
SC9-a		$165.2 \times 3.98 \times 495$	23,840	29.21	275.8	1530	1499	1.021
SC9-b		$164.8 \times 3.88 \times 495$	23,840	29.21	275.8	1566	1603	0.977
SC9-c		$165.0 \times 3.96 \times 495$	23,840	29.21	275.8	1545	1489	1.038
SC10-a		$164.7 \times 3.86 \times 495$	24,830	37.66	275.8	1667	1699	0.981
SC10-b		$164.5 \times 3.86 \times 495$	24,830	37.66	275.8	1634	1685	0.970
SC11-a		$163.9 \times 2.47 \times 495$	19,500	22.9	281.7	1113	1090	1.021
SC11-b		$163.9 \times 2.53 \times 495$	19,500	22.9	281.7	1123	1101	1.020
SC11-c		$164.4 \times 2.49 \times 495$	19,500	22.9	281.7	1122	1055	1.064
SC12-a		$113.3 \times 3.59 \times 342$	19,500	22.9	274.7	721	790	0.913
SC12-b		$113.5 \times 3.60 \times 342$	19,500	22.9	274.7	723	762	0.949
SC12-c		$113.1 \times 3.56 \times 342$	19,500	22.9	274.7	715	766	0.933
SC13-a		$164.5 \times 3.90 \times 495$	19,500	22.9	275.8	1335	1329	1.005
SC13-b		$164.3 \times 3.88 \times 495$	19,500	22.9	275.8	1329	1347	0.986
SC13-c		$164.6 \times 3.87 \times 495$	19,500	22.9	275.8	1331	1357	0.981
SC1-A		$163.9 \times 2.47 \times 495$	18,500	16.7	299.0	962	936	1.028
SC1-B		$164.0 \times 2.53 \times 495$	18,500	16.7	299.0	1033	1022	1.011
SC1-C		$164.4 \times 2.49 \times 495$	18,500	16.7	299.0	954	939	1.016
SC2-A		$113.4 \times 3.57 \times 342$	24,800	39.3	315.0	789	799	0.987
SC2-B		$113.3 \times 3.60 \times 342$	24,800	39.3	315.0	886	890	0.996
SC2-C		$113.0 \times 3.58 \times 342$	24,800	39.3	315.0	907	920	0.986
SC3-A	[15]	$113.5 \times 3.60 \times 342$	18,500	16.7	315.0	782	791	0.989
SC3-B		$113.1 \times 3.56 \times 342$	18,500	16.7	315.0	779	789	0.987
SC3-C		$113.3 \times 3.60 \times 342$	18,500	16.7	315.0	794	805	0.986
SC4-A		$164.5 \times 3.90 \times 495$	18,500	16.7	295.2	1251	1262	0.991
SC4-B		$164.3 \times 3.88 \times 495$	18,500	16.7	295.2	1254	1265	0.991
SC4-C		$164.6 \times 3.87 \times 495$	18,500	16.7	295.2	1248	1258	0.992
SC1-1-1a		$165.0 \times 1.32 \times 578$	19,600	22.9	226.7	675	665	1.015
SC1-1-2a		$165.0 \times 2.05 \times 578$	19,600	22.9	214.1	820	806	1.017
SC1-2-1a	[27]	$165.0 \times 1.32 \times 577$	23,400	29.3	226.7	785	801	0.980
SC1-2-2a		$165.0 \times 2.05 \times 577$	23,400	29.3	214.1	895	918	0.975
Mean	-	-	-	-	-	-	-	0.997
C.V.	-	-	-	-	-	-	-	0.034

The typical axial load–axial strain curves of the FE results and experimental results of Fu [14] were compared and shown in Figure 5a. The distribution curves of the axial load undertaken by the steel tube ($N_s - \epsilon$) and infilled concrete ($N_c - \epsilon$), the stress–strain curve of steel and infilled concrete, the curve of the transverse deformation coefficient, defined as the absolute value of the ratio of the transverse strain to the axial strain, for the steel tube in specimen SC10-a are shown in Figure 5b. It can be found that, generally, good agreement is achieved between the calculated FE curves and the test curves. The comparison of these curves indicate that the established model of LACFCST stub columns under axial compression and the plastic-damage constitutive model of LAC adopted in this study can precisely reproduce the test results and accurately simulate the mechanical behaviors of LAC in composite columns.

The load–strain curves of the FE results and experimental results in Zhu [27] are compared in Figure 6a, and the experimental strain curves shown in the figure represent the average values of four measuring points. The ratio of the axial load to the ultimate load (N/N_u)—the transverse deformation coefficient curves—are presented in Figure 6b. Based on this comparison, it can be seen that the strain responses obtained by the FEMs

coincide well with the experimental curves, which validate the applicability of the adopted elastoplastic constitutive model of steel tubes.

Figure 5. Comparison of FE and experimental curves about Fu [14]: (a) comparison of load–strain curves of SC1-c, SC5-b and SC8-b; (b) comparison of load–strain curves of SC2-b, SC3-b and SC9-b; (c) comparison of load–strain curves of SC10-a; (d) comparison of stress–strain curves of SC10-a.

3.2. Parametric Study

With the validated FEM, a parametric study was conducted. A total of 95 full-scale FEMs were established to investigate the mechanical behaviors and composite actions of the LACFCST stub columns subjected to axial compression. The parameters of all specimens were taken as the outer diameter of circular section $D = 500$ mm, and the length of the column $L = 1500$ mm; the wall-thicknesses of the steel tubes were set as $t = 6$ mm, 7 mm, 8 mm, 9 mm, and 10 mm, with the steel ratios ρ of 4.74%, 5.52%, 6.30%, 7.07%, 7.84%, respectively. The elastic modulus E_s was taken as 2.06×10^5 MPa, and the yield strength f_y of steel tube was taken as 235 MPa, 345 MPa, 390 MPa, 420 MPa, 460 MPa. The uniaxial compressive strength f_c of LAC was selected as 20 MPa, 30 MPa, 40 MPa, 50 MPa, 60 MPa, 70 MPa and 80 MPa, which covered the available strength in engineering practice [32]. With different wall-thicknesses of steel tubes, the strength of carbon steel and LAC were paired according to the reasonable strength grade collocation for the LACFCST stub column specimens. As shown in Table 3, $f_y = 235$ MPa was paired with $f_c = 20$ MPa, 30 MPa, 40 MPa, 50 MPa; $f_y = 345$ MPa was paired with $f_c = 30$ MPa, 40 MPa, 50 MPa, 60 MPa, and so on.

Figure 6. Comparison of FE and experimental curves about Zhu [27]: (a) comparison of load–strain curves of SC1-1-1a and SC1-1-2a; (b) comparison of load–strain curves of SC1-2-1a and SC1-2-2a; (c) comparison of load ratio–strain ratio curves of SC1-1-1a; (d) comparison of load ratio–strain ratio curves of SC1-1-2a.

Table 3. Parameters of specimens for FE parametric study.

D (mm)	L (mm)	E_s (MPa)	t (mm)	f_y (MPa)	f_c (MPa)
500	1500	20,600,0	6,7,8,9,10	235	20,30,40,50
				345	30,40,50,60
				390	40,50,60,70
				420	50,60,70,80
				460	60,70,80

The influence of the LAC strength, steel yield strength and steel ratio on the axial loading behaviors of the LACFCST stub columns are presented in Figure 7 in the manner of typical $N_{FE} - \varepsilon_L$ curves. The presented results indicate that these factors have a significant impact on the ultimate bearing capacity of the LACFCST stub columns under axial compression. The influence trends of these parameters are similar to that of CFCST stub columns [19].

3.3. Comparison of CFCST and LACFCST Columns

To investigate the difference between the composite action of CFCST and LACFCST columns under the compressive load, a full-scale FEM of CFCST stub columns with the exact same design parameters was established. The composite actions between the outer steel tube and two types of infilled concretes were evaluated by comparing the structural responses, as shown in Figure 8a–d. The load–strain curves of LACFCST and CFCST stub columns are drawn in Figure 8a, and they indicate that the ultimate bearing capacity of

LACFCST stub columns is slightly lower than that of CFCST stub columns with the same design parameters. In particular, the reduction is 4.6% in the presented case.

Figure 7. Influence of various parameters on the load-bearing capacity: (a) concrete strength; (b) steel yielding strength; (c) steel ratio.

Under axial compression, the infilled LAC is confined by the steel tube while the tube is influenced by the infilled LAC, as well. From this point of view, the performance of the composite columns cannot be only evaluated by the confinement effect exerted by the out tube. Ding et al. [33] reported that in the CFST columns, the axial stress decreases with the increase in transverse stress in the elastoplastic element of the steel tube under axial compression. Given this behavior, the composite action in composite columns can be assessed by the variation in the axial and transverse stress of the steel tube during the loading process (Figure 8b). If the axial stress curves intersect with the transverse stress, the degree of composite action is high. Furthermore, if the intersection occurs earlier, the degree of composite action in the CFST columns is stronger. As shown in Figure 8b, the intersection point of CFCST appears at the strain level of 0.01, but there is no intersection point of the axial and transverse stress of the outer steel tube of LACFCST stub columns. Figure 8c shows that the radial stress–strain curves of infilled concrete in LACFCST stub columns and CFCST counterparts, and the load—the transverse deformation coefficient ($N - \nu_{sc}$)—curves of the LACFCST stub column and CFCST stub column counterparts are plotted in Figure 8d. Given by Figure 8c,d, the radial stress of the LACFCST stub column is lower than that of CFCST stub column counterparts with the same axial strain level, and the load of the LACFCST stub column is lower than that of CFCST stub column counterparts with the same transverse deformation coefficient level, as well. These results revealed that the composite action between steel tubes and LAC is weaker than that between steel tubes and conventional concrete.

Figure 8. Comparison of typical curves for LACFCST and CFCST stub columns: (a) load–strain curves; (b) stress–strain curves of steel tubes; (c) radial stress–strain curves of core concrete; (d) load–strain ratio curves of steel tubes.

3.4. Composite Action Model of LACFCST Stub Columns

In the analytical modeling of axially-loaded CFST stub columns, the axial and transverse stress of steel tubes at the ultimate state are the key parameters to determine the load-bearing capacity. This is because the composite action between the steel tube and infilled concrete can be theoretically derived once these parameters are obtained. However, existing studies [5,34–39] assume that the von Mises yield criterion can be employed to define the ultimate state of the steel tube in composite columns:

$$\sigma_{L,s}^2 + \sigma_{\theta,s}^2 - \sigma_{L,s}\sigma_{\theta,s} = f_y^2 \quad (3)$$

where $\sigma_{L,s}$ and $\sigma_{\theta,s}$ represent the axial compressive stress and transverse tensile stress of the steel tube, respectively.

This may lead inaccurate prediction due to the following reasons. Firstly, based on the FE simulation, it is found that the metal tube may yield before or after the stub column reaches its ultimate state; in this situation, Equation (3) is invalid. Moreover, the stress component along the thickness direction is neglected, which means that Equation (3) is approximate, especially when the tube wall is thick. To compensate for this problem, the presented study extracts the axial and the transverse stress of the steel tube when the composite columns reach their ultimate state. Since the steel tube was modeled by the solid element, the three-dimensional stress state is considered.

The axial stress $\sigma_{L,s}$ and the transverse stress $\sigma_{\theta,s}$ of the steel tube at the mid-height section of all the FEMs at the ultimate state were captured. It can be found from Figure 9 that the distribution of $\sigma_{L,s}$ and $\sigma_{\theta,s}$ are highly correlated to the confinement factor ξ ($\xi = A_s f_y / A_c f_c$). Based on the FE analytical results, the numerical model of the composite

action in LACFCST stub columns are proposed in Equations (4) and (5) using the regression method. It should be noticed here that two independent formulas were proposed for $\sigma_{L,s}$ and $\sigma_{\theta,s}$, respectively, instead of using Equation (3).

$$\sigma_{L,s}/f_y = 0.027\zeta + 0.8655 \quad (4)$$

$$\sigma_{\theta,s}/f_y = 0.1029 \ln(\zeta) + 0.4939 \quad (5)$$

Figure 9. Influence of ζ on outer steel tubular stress: (a) the axial stress of outer steel tube; (b) the transverse stress of outer steel tube.

4. Practical Design Formula for the Load-Bearing Capacity of LACFCST Stub Columns

4.1. Model Simplification

The stress nephogram of infilled concrete of the mid-height section for LACFCST and CFCST stub columns was extracted from the FEMs and is presented in Figure 10. It indicates that the confinement effects of LACFCST and CFCST stub columns occur on the whole infilled concrete section and can be simplified in a method, as shown in Figure 11, where the steel tube in composite columns is subjected to multiple stresses under axial compression, in which D is the outer diameter of the steel tube, and D_0 is the inner diameter of the steel tube, A_s is the sectional area of the steel tube, A_c is the sectional area of the whole infilled concrete, $\sigma_{r,c}$ is the radial stress of concrete in the confined area, $\sigma_{\theta,s}$ is the transverse tensile stress of the steel tube, $\sigma_{L,s}$ is the axial compressive stress of the steel tube, and ρ is the steel ratio.

Figure 10. Comparison of stress nephogram at mid-height section for LACFCST and CFCST stub columns: (a) LACFCST stub column; (b) CFCST stub column.

Figure 11. Simplified stress distribution model at the mid-height section of LACFCST stub columns.

According to the equilibrium condition of the stress state shown in Figure 11, the following equations can be obtained [40]:

$$\sigma_{r,c} = \frac{\rho}{2(1-\rho)} \sigma_{\theta,s} \quad (6)$$

$$\rho = \frac{D^2 - D_0^2}{D^2} \quad (7)$$

4.2. Formulation

Ding et al. [33] reported that the axial compressive stress ($\sigma_{L,c}$) of confined infilled concrete can be described as:

$$\sigma_{L,c} = f_c + k\sigma_{r,c} \quad (8)$$

where k is the coefficient of lateral pressure according to the cross-section type, while for the circular section, $k = 3.4$.

On the basis of the static equilibrium method, the ultimate bearing capacity N_u of axially loaded LACFCST stub columns can be expressed as [34]:

$$N_u = \sigma_{L,c}A_c + \sigma_{L,s}A_s \quad (9)$$

Substituting Equations (4)–(8) into Equation (9), the ultimate bearing capacity N_{u1} can be obtained as:

$$N_{u1} = f_y A_s (1/\xi + 0.027\xi + 0.1749 \ln(\xi) + 1.7052) \quad (10)$$

In the analytical study, when the specimen reached the ultimate state, the axial stress $\sigma_{L,s}$ to yield strength f_y ratio and the transverse stress $\sigma_{\theta,s}$ to yield strength f_y ratio of the outer steel tube were calculated and are plotted in Figure 12 with the nominal average axial stress f_{sc} ($f_{sc} = N_u/A_{sc}$, $A_{sc} = A_s + A_c$) as the abscissa. Based on the analytical results of 95 specimens with different design parameters, it can be seen from Figure 12 that the average ratio of axial stress to yield strength is 0.87, which is greater than 0.69 of CFCST stub columns, and the average ratio of transverse stress to yield strength is 0.41, which is lower than 0.55 of CFCST stub columns [19].

To simplify the calculation process, the average ratio of $\sigma_{L,s}/f_y$ and $\sigma_{\theta,s}/f_y$ can be employed instead of Equations (4) and (5). As shown in Figure 12a,b, when LACFCST stub columns reach the ultimate bearing capacity, the average ratio of axial compressive stress ($\sigma_{L,s}$) to yield strength, and transverse tensile stress ($\sigma_{\theta,s}$) to yield strength of the steel tube can be obtained as:

$$\sigma_{L,s} = 0.87f_y \quad (11)$$

$$\sigma_{\theta,s} = 0.41f_y \quad (12)$$

Substituting Equations (6)–(8) and Equations (11) and (12) into Equation (9), the ultimate bearing capacity N_{u2} can be obtained as:

$$N_{u2} = f_c A_c + K f_y A_s \quad (13)$$

where K is the enhancement factor [41], which reflects the enhancement effect provided by the infilled concrete to the outer tube. For LACFCST stub columns, $K = 1.57$ is slightly smaller than $K = 1.62$ of CFCST stub columns [19].

Figure 12. Analytical results of axial stress and transverse stress of outer steel tube of LACFCST stub column: (a) average ratio of axial stress to yield strength of steel tubes; (b) average ratio of transverse stress to yield strength of steel tubes.

4.3. Formulas Validation

The ultimate bearing capacities calculated from Equation (10) (N_{u1}) and Equation (13) (N_{u2}) were compared with collected 49 experimental specimens results ($N_{u,Exp}$) in references [14,15,27], as shown in Figure 13. The average ratios of N_{u1} and N_{u2} to $N_{u,Exp}$ is 1.031 and 0.967 with the corresponding C.V. of 0.092 and 0.072, respectively. The consequences of Equations (10) and (13) showed that there is nearly no difference using these two formulas to calculate the ultimate bearing capacity of the LACFCST stub columns. Equation (13) has a relatively conservative calculation result and a simple form, which is beneficial to its application in practical engineering.

Figure 13. Comparison of Equations (10) and (13): (a) comparison of the ultimate bearing capacities obtained from test results and Equation (10); (b) comparison of the ultimate bearing capacities obtained from test results and Equation (13).

The ultimate bearing capacities of 95 full-scale FEMs, calculated from Equation (13) (N_{u2}), and FE results ($N_{u,FE}$) were compared, as shown in Figure 14. The average ratio of N_{u2} to $N_{u,FE}$ is 1.038 with the corresponding C.V. of 0.018, which means the FEM analytical results and the proposed Equation (13) have good agreement.

Figure 14. Comparison of the ultimate bearing capacities obtained from FE results and Equation (13).

To evaluate the performance of the proposed design equation, three methods, suggested by the current design codes for the normal strength CFCST stub columns as shown in Table 4, were used to calculate the bearing capacity of the collected 49 experimental specimens in references [14,15,27]. Those widely used design codes employed in this study, include the GB 50936 [42] for China, the EC 4 [11] for Europe and ACI-318 [12] for the United States. The results, N_{u2} , N_{GB} , N_{EC} , and N_{ACI} , calculated by the proposed Equation (13) and three codes, respectively, are listed in Figure 15 and Table 5. It can be seen from Table 5 that the average values of the ratios ($N_{u2}/N_{u,Exp}$, $N_{GB}/N_{u,Exp}$, $N_{EC}/N_{u,Exp}$, and $N_{ACI}/N_{u,Exp}$) are 0.967, 1.009, 0.933, 0.729 with a C.V. of 0.072, 0.088, 0.086, and 0.079 respectively. The results revealed that the accuracy of the proposed equation is comparable to GB 50,936 [42] and EC 4 [11], and higher than that of ACI-318 [12]. On the other hand, the formula proposed in this paper is simple, and its physical meaning is clear.

Figure 15. Comparison of the ultimate bearing capacities obtained from test results and equations.

Table 4. Summary of available formulas in well-known national codes.

References	Formulas	Addition
GB 50936 (2014) [42]	When $\theta \leq 1/(\alpha - 1)^2$, $N_{GB} = 0.9A_c f_c (1 + \alpha\theta)$;	$\theta = \frac{A_s f_y}{A_c f_c}$
	When $\theta > 1/(\alpha - 1)^2$, $N_{GB} = 0.9A_c f_c (1 + \sqrt{\theta} + \theta)$	If $f_{cu} \leq 50$ MPa, $\alpha = 2.0$ If $50 \text{ MPa} \leq f_{cu} \leq 80$ MPa, $\alpha = 1.8$
EC 4 (2004) [11]	$N_{EC4} = \eta_\alpha f_y A_s + f'_c A_c \left(1 + \eta_c \frac{t f_y}{D f'_c}\right)$	$\eta_\alpha = 0.25(3 + 2\bar{\lambda}) \leq 1.0$
		$\eta_c = 4.9 - 18.5\bar{\lambda} + 17\bar{\lambda}^2 \geq 1.0$ $\bar{\lambda} = \sqrt{\frac{N_{pl,Rk}}{N_{cr}}}$, $N_{pl,Rk} = \sigma_{0.2} A_s + f'_c A_c$ $N_{cr} = \frac{\pi^2 (E_s I_s + 0.6 E_c I_c)}{L^2}$
ACI-318 (2011) [12]	$N_{ACI} = f_y A_s + 0.85 f'_c A_c$	

Table 5. Comparison between experimental and predicted results using different design methods.

Specimens	Ref.	N_{u2} (kN)	N_{GB} (kN)	N_{EC} (kN)	N_{ACI} (kN)	$N_{u,Exp}$ (kN)	$N_{u2}/$ $N_{u,Exp}$	$N_{GB}/$ $N_{u,Exp}$	$N_{EC}/$ $N_{u,Exp}$	$N_{ACI}/$ $N_{u,Exp}$
SC1-a		599	622	627	485	659	0.909	0.943	0.951	0.737
SC1-c		612	637	639	494	675	0.907	0.943	0.947	0.732
SC2-a		680	696	685	537	738	0.921	0.943	0.928	0.728
SC2-b		699	718	702	549	689	1.015	1.042	1.019	0.797
SC2-c		688	705	692	542	678	1.015	1.040	1.020	0.799
SC3-a		821	828	830	624	852	0.963	0.972	0.975	0.733
SC3-b		818	826	828	623	822	0.996	1.005	1.007	0.758
SC4-a		893	930	879	670	884	1.010	1.052	0.994	0.758
SC4-b		897	933	883	672	889	1.009	1.049	0.993	0.756
SC4-c		888	925	874	667	899	0.987	1.029	0.973	0.742
SC5-b		1175	1204	1304	978	1214	0.968	0.992	1.074	0.806
SC5-c		1147	1172	1276	961	1403	0.818	0.835	0.909	0.685
SC6-a		1339	1351	1370	1082	1475	0.908	0.916	0.929	0.733
SC6-c		1309	1314	1344	1065	1540	0.850	0.853	0.873	0.692
SC7-a		1288	1333	1357	1051	1410	0.914	0.945	0.962	0.745
SC7-b		1289	1335	1357	1050	1340	0.962	0.996	1.013	0.784
SC7-c	[14]	1311	1360	1377	1064	1547	0.847	0.879	0.890	0.688
SC8-b		1469	1501	1483	1162	1647	0.892	0.911	0.900	0.706
SC8-c		1444	1471	1462	1149	1629	0.886	0.903	0.897	0.705
SC9-a		1440	1511	1498	1141	1530	0.941	0.988	0.979	0.746
SC9-b		1415	1483	1474	1125	1566	0.904	0.947	0.941	0.718
SC9-c		1434	1504	1491	1137	1545	0.928	0.973	0.965	0.736
SC10-a		1573	1624	1583	1225	1667	0.944	0.974	0.949	0.735
SC10-b		1571	1621	1579	1223	1634	0.961	0.992	0.967	0.748
SC11-a		1008	1044	1012	768	1113	0.906	0.938	0.909	0.690
SC11-b		1021	1059	1024	776	1123	0.909	0.943	0.912	0.691
SC11-c		1017	1054	1021	774	1122	0.907	0.939	0.910	0.690
SC12-a		736	724	716	525	721	1.021	1.005	0.993	0.728
SC12-b		739	727	719	527	723	1.023	1.006	0.994	0.729
SC12-c		730	719	710	521	715	1.021	1.006	0.993	0.729
SC13-a		1294	1327	1278	946	1335	0.969	0.994	0.957	0.709
SC13-b		1287	1321	1271	942	1329	0.969	0.994	0.957	0.709
SC13-c		1289	1323	1273	943	1331	0.968	0.994	0.957	0.709
SC1-A		919	952	793	633	962	0.956	0.990	0.824	0.658
SC1-B		934	964	804	642	1033	0.904	0.934	0.778	0.622
SC1-C		928	961	800	639	954	0.973	1.007	0.839	0.670
SC2-A		958	994	807	690	789	1.214	1.260	1.022	0.875
SC2-B		961	996	808	692	886	1.085	1.124	0.912	0.781
SC2-C		954	990	803	687	907	1.052	1.091	0.885	0.758
SC3-A	[15]	763	838	604	507	782	0.976	1.072	0.772	0.649
SC3-B		753	827	596	501	779	0.967	1.062	0.766	0.643
SC3-C		761	836	602	506	794	0.959	1.053	0.759	0.637
SC4-A		1234	1335	1021	832	1251	0.986	1.067	0.816	0.665
SC4-B		1228	1328	1016	828	1254	0.979	1.059	0.810	0.660
SC4-C		1228	1329	1017	829	1248	0.984	1.065	0.815	0.664
SC1-1-1a		716	808	681	547	675	1.060	1.197	1.009	0.810
SC1-1-2a		818	912	777	610	820	0.998	1.113	0.947	0.744
SC1-2-1a	[27]	848	959	848	693	785	1.081	1.222	1.081	0.883
SC1-2-2a		949	1068	939	754	895	1.060	1.193	1.050	0.843
Mean	-	-	-	-	-	-	0.967	1.009	0.933	0.729
C.V.	-	-	-	-	-	-	0.072	0.088	0.086	0.079

5. Conclusions

The objective of this paper is to investigate the confinement effects of LACFCST stub columns under axial loading. The main findings are summarized as follows:

1. Using a plastic-damage constitutive model of LAC and an elastoplastic model with isotropic strain hardening of the steel tube, a fine-meshed finite 3D solid element model of the LACFCST stub column was established in ABAQUS. The validity of the established FEM was verified against the test results of the ultimate bearing capacity and strain responses of the steel tube, and the load-shortening curves.
2. A total of 95 full-scale FEMs, using the abovementioned FE modeling method, were established for the parametric study. The analytical results revealed that the composite action in LACFCST stub columns is weaker than that in CFST stub columns.
3. Regression models of the axial and transverse stress of the outer steel tube at the ultimate state of the columns were proposed, respectively. This model considered the three-dimensional stress state of the outer tube and is a more authentic expression when the column reaches its ultimate state.
4. A design formula of ultimate bearing capacity of LACFCST stub columns under axial loading was derived based on the proposed composite action model. A simplified formula using an enhancement factor was proposed as well. The derived enhancement factor of LACFCST stub columns is 1.57, which is slightly smaller than 1.62 of CFST stub columns. The proposed formula was verified as more accurate and concise than current design methods.

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Nomenclature

A_c	Cross-sectional area of infilled concrete
A_s	Cross-sectional area of steel tube
A_{sc}	Cross-sectional area of LACFCST column
D	Outer diameter of steel tube
D_0	Inner diameter of steel tube
E_s	Elastic modulus of steel tube
f_c	Uniaxial compressive strength of LAC
f_{cu}	Compressive cubic strength of LAC
f_{sc}	Nominal average axial stress
f_u	Ultimate strength of steel tube
f_y	Yield strength of steel tube
K	Enhancement factor
L	Length of column specimen
N_{ACI}	Ultimate bearing capacity calculated by ACI-318
N_{EC}	Ultimate bearing capacity calculated by EC 4
N_{GB}	Ultimate bearing capacity calculated by GB 50936
N_u	Ultimate bearing capacity of stub columns
$N_{u,Exp}$	Ultimate bearing capacity obtained from test
$N_{u,FE}$	Ultimate bearing capacity obtained from FEMs
t	Wall-thickness of steel tube
ζ	Confinement factor

ρ	Steel ratio of LACFCST column
ε_c	Strain at the peak compressive stress
ε_L	Longitudinal strain of steel tube
ε_{st}	Hardening strain of steel tube
ε_u	Ultimate strain of steel tube
ε_y	Yield strain of steel tube
$\sigma_{L,c}$	Axial compressive stress of infilled concrete
$\sigma_{L,s}$	Axial compressive stress of steel tube
$\sigma_{r,c}$	Radial stress of infilled concrete
$\sigma_{\theta,s}$	Transverse tensile stress of steel tube
ν_{sc}	Transverse deformation coefficient

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