AXIAL STRENGTH OF CFST COLUMNS CONSIDERING CONCRETE AGE

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ABSTRACT: Concrete filled steel tube (CFST) columns are used increasingly in high-rise buildings in China. During the rapid construction of high-rise buildings, concrete age is an important factor which will affect the composite axial strength. In this paper, based on the theory of elasticity, a formula is proposed to predict the composite axial strength of CFST considering the concrete age. For the most common use the parameters in the formula are simplified and calibrated by existing test results. Finally the experiments of the ultimate bearing capacity of CFST columns considering concrete age changes are carried out and the FE method is also adopted to validate the formula results. The results show that the formula can be used satisfactorily in predicting the strength of CFST columns considering concrete age.

Keywords: CFST, composite strength, concrete age, axial strength

1. INTRODUCTION

The concrete filled steel tube (CFST) structure is widely used now around the world because of its superior property on mechanics, fire resistance, anti seismic capacity as well as its cost effective construction. Extensive experimental and theoretical investigations on the CFST have been carried out [1-8]. In recent years, more and more high-rise buildings are constructed using CFST columns mentioned by Fu [9], Fan [10] and Duan [11]. The advantage is to adopt rapid construction which the inside concrete is not fully hardened during the construction and the building is be set up by the outside steel tube frame. This kind of construction method can greatly reduce the time but also bring a problem that the composite strength of CFST column may be different being of the earlier age of concrete.

On the influence of concrete age, Tan and Qi [12] worked systematically by testing the effect of creep on columns under axially compressive loads. Nakai et al. [13] and Terry et al. [14] tested the creep of CFST columns and plain concrete to investigate the influence of the reinforcement on the concrete creep. Ichinose et al. [15], Kwon et al. [16] and Acar [17] also reported a series of tests to obtain creep coefficients of CFST columns. But nearly all of the works are about the aging effect of hardened concrete and there is little attention paid to the research on the aging effect of hardening CFST column.

In this paper, the aging effect of un-fully hardened concrete will be studied on the composite strength of CFST columns and a formula will be proposed based on the theory of elasticity by using the superimposition method and test results. Independent experiments and FE method are also adopted to validate the formula.

2. THEORY ANALYSIS

2.1 Superimposition method

In order to determine the formula of composite strength of CFST columns under axial compression, the elastic analysis is adopted. The CFST column can be equivalently divided into two parts. i.e., the steel tube and the concrete part, and the axial compression process can be divided into two steps. i.e., uniaxial compression of each part and plane strain problem according to Yu [18]. In the uniaxial compression step, two parts are deformed individually as the uniform longitudinal strain. In the second step, there will be the interaction load between the two parts but the longitudinal strain of each part keeps constant which is the plane strain problem, shown in Figure 1.

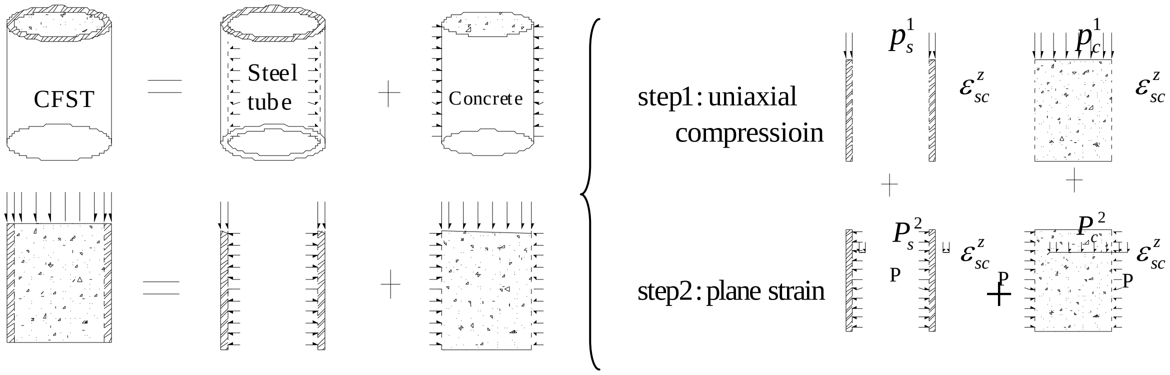


Figure 1. Superimposition Method of CFST under Axial Compression

2.2 Elastic Analysis

Assume that the longitudinal strain of the CFST is $\varepsilon_{sc}^z(t)$ under the compression load, as a whole. The longitudinal strains in the steel tube $\varepsilon_s^z(t)$ and the concrete $\varepsilon_c^z(t)$ should be the same, then

$$\varepsilon_s^z(t) = \varepsilon_c^z(t) = \varepsilon_{sc}^z(t) \tag{1}$$

Step 1: The uniaxial compression stage

In this stage, because of the no interactions between steel and concrete, steel tube and concrete cylinder are unrestrained axisymmetric deformation. According to the generalized Hooke's law the radial strains are:

$$\varepsilon_c^r(t) = -\nu_c(t)\varepsilon_{sc}^z(t) \tag{2}$$

$$\varepsilon_s^r(t) = -\nu_s\varepsilon_{sc}^z(t) \tag{3}$$

In which, $\nu_c(t)$ is the Poisson's ratio of concrete at age t, and ν_s is the Poisson's ratio of steel. According to Budynas [19], when the radius at the interface surface is r, the radial displacements $u_c^1(t)$ at the outside surface of the concrete cylinder and u_s^1 at the inside surface of the steel tube, are respectively,

$$u_c^1(t) = r\varepsilon_c^r(t) = -\nu_c(t) r\varepsilon_{sc}^z(t) \tag{4}$$

$$u_s^1(t) = r\varepsilon_s^r(t) = -\nu_s r\varepsilon_{sc}^z(t) \tag{5}$$

So the respective longitudinal stresses of the concrete $\sigma_c^1(t)$ and the steel $\sigma_s^1(t)$ are,

$$\sigma_c^1(t) = E_c(t)\varepsilon_c^z(t) = E_c(t)\varepsilon_{sc}^z(t) \tag{6}$$

$$\sigma_s^1(t) = E_s\varepsilon_s^z(t) = E_s\varepsilon_{sc}^z(t) \tag{7}$$

In which, $E_c(t)$ is the elastic modulus of concrete at age t, and E_s is the elastic modulus of steel.

Step 2: The plane strain stage

In this stage the longitudinal strain is constant and there is the interactive stress P acting between the inside surface of the steel tube and the outside surface of the concrete. According to the theory of elasticity [20], the radial displacements of the concrete cylinder at the outside surface $u_c^2(t)$, and the radial displacements of the steel tube at the inside surface u_s^2 can be calculated respectively,

$$u_c^2(t) = -\frac{r^2 P}{\frac{E_c(t)}{1-\nu_c^2(t)} r^2}\left(1 - \frac{\nu_c(t)}{1-\nu_c(t)}\right) r = -\frac{(1+\nu_c(t))(1-2\nu_c(t))}{E_c(t)} rP \tag{8}$$

$$u_s^2 = \frac{(1+\nu_s) r^2 P}{E_s(R^2 - r^2)}\left[\frac{R^2}{r} + (1-2\nu_s) r\right] \tag{9}$$

In which, R is the radius at the outside surface of the steel tube.

Step 3: Superimposition results

Assume that the interfaces are ideal and continuous at the interfaces of the steel tube and concrete part. So the radial displacements of steel part and the concrete part should be same at the interfaces,

$$u_c^1(t) + u_c^2(t) = u_s^1 + u_s^2 \tag{10}$$

Introducing Eqs. 4, 5, 8 and 9 into Eq. 10 yields the interactive stress P at the interface,

$$P = \frac{-(\nu_c(t) - \nu_s)\varepsilon_{sc}^z(t)}{\frac{(1+\nu_c(t))(1-2\nu_c(t))}{E_c(t)} + \frac{(1+\nu_s)}{E_s(R^2 - r^2)}[R^2 + r^2(1-2\nu_s)]} \tag{11}$$

From the elastic solution from Sadd [20], the longitudinal stresses caused by P in the concrete part $\sigma_c^2(t)$, and the steel tube $\sigma_s^2(t)$, are,

$$\sigma_c^2(t) = -2\nu_c(t) P \tag{12}$$

$$\sigma_s^2(t) = \frac{2\nu_s r^2}{R^2 - r^2} P \tag{13}$$

Hence, the total longitudinal stresses in the concrete and the steel tube are, respectively,

$$\sigma_c(t) = \sigma_c^1(t) + \sigma_c^2(t) = E_c(t)\varepsilon_{sc}^z(t) - 2\nu_c(t)P \tag{14}$$

$$\sigma_s(t) = \sigma_s^1 + \sigma_s^2 = E_s\varepsilon_{sc}^z(t) + \frac{2\nu_s r^2}{R^2 - r^2}P \tag{15}$$

Introducing Eq. 11 into Eq. 14 and Eq. 15, the equivalent uniform stress distribution $\sigma_{sc}(t)$ over the cross section of the CFST is ,

$$\sigma_{sc}(t) = \frac{A_s\sigma_s(t) + A_c\sigma_c(t)}{A_{sc}} \tag{16}$$

Thus,

$$\sigma_{sc}(t) = \left[1 + \frac{2(\nu_c - \nu_s)^2\alpha\,\sigma_s^1/\sigma_c^1(t)}{\left[(1-2\nu_c)(1+\nu_c)\alpha\,\sigma_s^1/\sigma_c^1(t) + 2(1-\nu_s^2) + (1+\nu_s)\alpha\right]\left(1 + \alpha\,\sigma_s^1/\sigma_c^1(t)\right)}\right]\left[(1-\beta)\sigma_c^1(t) + \beta\sigma_s^1\right] \tag{17}$$

Replacing all terms containing Poisson's ratios of steel and concrete by A, B and C, Eq. 17 can be written as below,

$$\sigma_{sc}(t) = \left[1 + \frac{\alpha\sigma_s^1/\sigma_c^1(t)}{\left[A + B\alpha\sigma_s^1/\sigma_c^1(t) + C\alpha\right]\left(1 + \alpha\sigma_s^1/\sigma_c^1(t)\right)}\right]\left[(1-\beta)\sigma_c^1(t) + \beta\sigma_s^1\right] \tag{18}$$

where, $A = \frac{(1-\nu_s^2)}{(\nu_c - \nu_s)^2}$, $B = \frac{(1-2\nu_c)(1+\nu_c)}{2(\nu_c - \nu_s)^2}$, $C = \frac{(1+\nu_s)}{2(\nu_c - \nu_s)^2}$, $\beta = \alpha/(1+\alpha)$.

2.3 Composite Strength of the CFST and Further Modification

In order to obtain the composite strength of CFST column in inelastic state, it is assumed that the strength of the steel and the concrete are reached simultaneously and introducing the strength of steel and concrete f_y , $f_{ck}(t)$ and parameter $\xi_{sc}(t) = \alpha f_y / f_{ck}(t)$. So,

$$f_{sc}(t) = \left[1 + \frac{\xi_{sc}(t)}{\left[A + B\xi_{sc}(t) + C\alpha\right]\left(1 + \xi_{sc}(t)\right)}\right]\left[(1-\beta)f_{ck}(t) + \beta f_y\right] \tag{19}$$

The influence of concrete age on concrete Poisson's ratio is very little according to Oluokun et al. [21] and Carmichael [22], so the concrete Poisson's ratio can be determined by test results of hardened CFST column which is at the age of 28 days. To statistically obtain estimated values of A, B, and C, standard regression analysis is carried out on the basis of a rich collection of test results from O'Shea et al. [3] and Kenji et al. [23]. Finally the values of the three constants are $A = 2.0$, $B = 0.01$, $C = 0.2$ as showing Table 1 and the results agree well.

Table 1. Comparison of the Analytical and the Test Results

Ref.	No.	Numbering	Geometric parameters		material parameters		Ultimate force		ratio
			External diameter D /mm	Steel thickness T /mm	f_y /Mpa	f_{ck} /Mpa	Test N_T /kN	Calc N_c /kN	N_T/N_c
[3]	1	S30CS50B	165	2.8	363.3	48.3	1662	1744	1.05
	2	S20CS50A	190	1.9	256.4	41	1678	1556	0.93
	3	S16CS50B	190	1.5	306.1	48.3	1695	1739	1.03
	4	S12CS50A	190	1.1	185.7	41	1377	1322	0.96
	5	S10CS50A	190	0.9	210.7	41	1350	1303	0.97
	6	S30CS80A	165	2.8	363.3	80.2	2295	2381	1.04
	7	S20CS80B	190	1.9	256.4	74.7	2592	2473	0.95
	8	S16CS80A	190	1.5	306.1	80.2	2602	2615	1.00
	9	S12CS80A	190	1.1	185.7	80.2	2295	2407	1.05
	10	S10CS80B	190	0.9	210.7	74.7	2451	2241	0.91
[3]	11	S30CS10A	165	2.8	363.3	108	2673	2935	1.10
	12	S20CS10A	190	1.9	256.4	108	3360	3379	1.01
	13	S16CS10A	190	1.5	306.1	108	3260	3378	1.04
	14	S12CS10A	190	1.1	185.7	108	3058	3176	1.04
	15	S10CS10A	190	0.9	210.7	108	3070	3168	1.03
[23]	16	CC4-A-2	149	3	308	21.5	941	971	1.03
	17	CC4-A-4-1	149	3	308	33.1	1064	1159	1.09
	18	CC4-A-4-2	149	3	308	33.1	1080	1159	1.07
	19	CC4-A-8	149	3	308	61.2	1781	1610	0.90
	20	CC4-C-2	301	3	279	21.5	2382	2629	1.10
	21	CC4-C-4-1	300	3	279	33.6	3277	3438	1.05
	22	CC4-C-4-2	300	3	279	33.6	3152	3438	1.09
	23	CC4-C-8	301	3	279	63.8	5540	5522	1.00
	24	CC4-D-2	450	3	279	21.5	4415	5069	1.15
	25	CC4-D-4-1	450	3	279	33.6	6870	6944	1.01
	26	CC4-D-4-2	450	3	279	33.6	6985	6944	0.99
	27	CC4-D-8	450	3	279	67.6	11665	12213	1.05
	28	CC6-A-2	122	4.5	576	21.5	1509	1655	1.10
	29	CC6-A-4-1	122	4.5	576	33.1	1657	1771	1.07
	30	CC6-A-4-2	122	4.5	576	33.1	1663	1771	1.06
	31	CC6-A-8	122	4.5	576	61.2	2100	2052	0.98
	32	CC6-C-2	239	4.5	507	21.5	3035	3429	1.13
	33	CC6-C-4-1	238	4.5	507	33.1	3583	3890	1.09
	34	CC6-C-4-2	238	4.5	507	33.1	3647	3890	1.07
	35	CC6-C-8	238	4.5	507	61.2	5578	5044	0.90
	36	CC6-D-2	361	4.5	525	21.5	5633	6088	1.08

	37	CC6-D-4-1	361	4.5	525	33.6	7260	7266	1.00
	38	CC6-D-4-2	360	4.5	525	33.6	7045	7237	1.03
	39	CC6-D-8	360	4.5	525	67.6	11505	10526	0.91
	40	CC8-A-2	108	6.5	853	21.5	2275	2768	1.22
	41	CC8-A-4-1	109	6.5	853	33.1	2446	2882	1.18
	42	CC8-A-4-2	108	6.5	853	33.1	2402	2851	1.19
	43	CC8-A-8	108	6.5	853	61.2	2713	3050	1.12
	44	CC8-C-2	222	6.5	843	21.5	4964	6254	1.26
	45	CC8-C-4-1	222	6.5	843	33.1	5638	6654	1.18
	46	CC8-C-4-2	222	6.5	843	33.1	5714	6654	1.16
	47	CC8-C-8	222	6.5	843	61.2	7304	7617	1.04
	48	CC8-D-2	337	6.5	823	21.5	8475	10045	1.19
	49	CC8-D-4-1	337	6.5	823	33.6	9668	11044	1.14
	50	CC8-D-4-2	337	6.5	823	33.6	9835	11044	1.12
	51	CC8-D-8	337	6.5	823	67.6	13776	13849	1.01

Thus, the composite strength of CFST column considering the age is simplified as shown in Eq.(20), in which $M = 0.001\xi_{sc}(t) + 0.2\alpha$.

$$f_{sc}(t) = \left[1 + \frac{\xi_{sc}(t)}{[2+M]\left(1+\xi_{sc}(t)\right)}\right]\left[(1-\beta) f_{ck}(t) + \beta f_y\right] \tag{20}$$

In practice, the range of steel grade is Q235 to Q420, and concrete is C30 to C80, the range of $f_y / f_{ck}(t)$ is 4.7 to 20.9. The range of steel ratio of CFST is from 0.04 to 0.2, Thus, the range of M is from 0.008 to 0.04 and $1/(2+M) \approx 0.5$. Also according to ACI209 [24], there is a relationship between the strength of hardened and hardening concrete,

$$f_{ck}(t) = Q(t) f_{ck} \tag{21}$$

$$Q(t) = \frac{t}{4+0.85t} \tag{22}$$

Then, the composite strength of CFST column considering concrete age can be expressed as following,

$$\begin{aligned} f_{sc}(t) &= \left[1 + \frac{0.5\xi_{sc}(t)}{\left(1+\xi_{sc}(t)\right)}\right]\left[(1-\beta) f_{ck}(t) + \beta f_y\right] = \frac{Q(t)+1.5\xi_{sc}^0}{1+\alpha} f_{ck} \\ &= \frac{\frac{t}{4+0.85t} + 1.5\xi_{sc}^0}{1+\alpha} f_{ck} \end{aligned} \tag{23}$$

In which, $\xi_{sc}^0 = \alpha f_y / f_{ck}$, and f_{ck} is the strength of hardened concrete.

3. Experiments and FE Analysis

In order to validate the formula of composite strength of CFST column considering concrete age of different hardening time, experiments and FEM are used in this section.

3.1 FE Model of CFST Columns

The software Abaqus is adopted to establish the FE Model. In the model, the 8-node quadrilateral in-plane general purpose continuum shell element (SC8R) is used for the steel tube, and the 8-node linear brick element (C3D8R) is used for the concrete. The bilinear material model is adopted for the steel, with the tangent modulus being one percent of the Elastic Modulus of 206GPa. The material model of the concrete is the damaged plasticity (DP) model with dilation angle being 40^{o}, and the strength of the concrete at different hardening time follows the curves proposed by Yi [25], as Eq. (24). Other material and geometrical parameters of the column are given in Table 2. According to the experimental specimen in Figure 2, the FE meshes of a typical CFST column are shown in Figure 3. It is assumed that the contact between the steel tube and the concrete is perfect. In order to study the convergent of the FEM model, different meshing schemes are tried which are listed in Table 3.

$$f_c\,(t) = \frac{\beta_m(\varepsilon_c / \varepsilon_c^{'})}{\beta_m - 1 + (\varepsilon_c / \varepsilon_c^{'})^{\beta_m}} f_c^{'} \tag{24}$$

$$\beta_m = \beta_{m,a} = \left[1.02 - 1.17(E_0 / E_c)\right]^{-0.74} \quad , \varepsilon_c < \varepsilon_c^{'} \tag{25}$$

$$\beta_m = \beta_{m,d} = \beta_{m,a} + (a + bt) \quad , \quad \varepsilon_c \ge \varepsilon_c^{'} \tag{26}$$

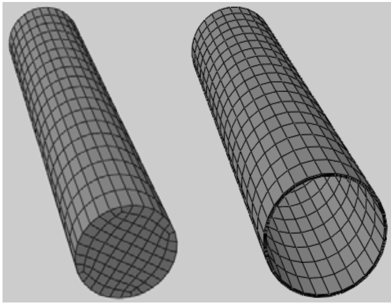
$$a = \left(12.4 - 1.66\times 10^{-2} f_{c,28}\right)^{-0.46} \tag{27}$$

$$b = 0.83\exp(-911/ f_{c,28}) \tag{28}$$

Where,

t	——	the age of concrete in day;
$f_c\,(t)$, ε_c	——	concrete stress and strain to be computed;
$f_c^{'}$, $\varepsilon_c^{'}$	——	maximum stress and corresponding strain of concrete at t days;
E_0	——	the secant modulus at the maximum stress, $E_0 = f_c^{'} / \varepsilon_c^{'}$;
E_c	——	elastic modulus of concrete;
$\beta_{m,a}$	——	a parameter of concrete for the ascending branch;
$\beta_{m,d}$	——	a parameter of concrete for the descending branch.

Figure 2. Experimental Specimens of CFST



a) concrete b) Steel tube

Figure 3. Finite Element Mesh of CFST Member

Table 2. Geometry and Material Parameters of CFST Column

D (mm)	T (mm)	L (mm)	f_y (MPa)	f_{ck} (MPa)	E_s (MPa)
219	5.5	766	355	51.2	2.06e5
133	4.5	400	345	40.8	2.06e5

Table 3. The Ultimate Load of Different Meshing Scheme

Model	N-Ring	N-Radius	N-Axial	E-Section	E-Tolal	N-3d (kN)	N-28d (kN)
M1	12	2,3	18	56	1120	2240	2868
M2	12	3,4	18	68	1224	2256	2904
M3	16	3,4	18	96	1728	2285	2942
M4	20	3,4	18	104	1872	2358	2965
M5	24	3,4	18	132	2376	2372	2972
M6	28	3,4	18	160	2880	2377	2979

In Table 3, N-Ring, N-Radius, and N-Axial are the respective numbers of elements in the circumferential, radial, and axial directions. E-Section and E-Total are the total numbers of elements on a cross section and of the whole column, respectively. N-3d and N-28d are the ultimate axial loads of the column at the age of 3 and 28 days. It can be seen that when the element mesh is finer than M4, smaller difference between the different meshing schemes are observed. It is decided therefore that the mesh scheme M4 will be used in the following numerical simulations.

Figure 4. Load Bearing Capacity Experiment of the CFST Column

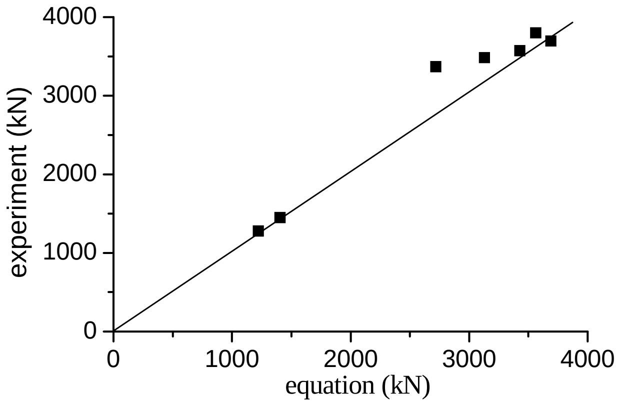


Fig.5 calculated value compared with experiment

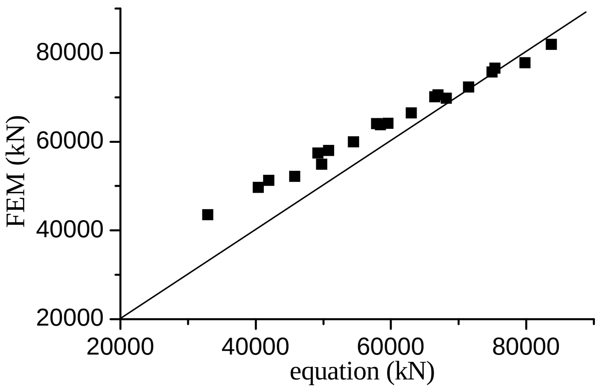


Figure 6. Calculated Value Compared with FEM

3.2 Validation of the Formula

Laboratory experiments had been carried out, as shown in Figures 2 and 4, and the specimen configuration details are specified in Table 2. The load bearing capacity experiments were taken at the concrete curing ages of 3, 7, 14, 21, 35 and 49 days.

The experimental results of the time-dependent elastic modulus of concrete at different ages are shown in Table 4. The comparison between equation results N_c, experimental results N_t and FE results N_f are showed in Table 5, 6 and Figure 5, 6. And the mean value is 0.945 and standard deviation is 0.06 which indicate the formula can predict well the composite strength of CFST columns by considering the variation of concrete curing age.

Table 4. Elastic Modulus of the Concrete at Different Age

age(day)	3	7	14	21	28
E_c (MPa)	30680	32319	34053	35101	35905

Table 5. Further Comparisons of Analytical Results with the Tests Results

No.	D /mm	T /mm	f_y /MPa	f_{ck} /MPa	t /day	f_{sc} /MPa	N_c /kN	N_t /kN	N_c/N_t
1	219	5.5	355	22.626	3	72.21	2719	3368.3	0.807
2	219	5.5	355	34.754	7	83.15	3131	3484	0.899
3	219	5.5	355	43.497	14	91.04	3428	3572.7	0.959
4	219	5.5	355	47.478	21	94.63	3563	3797.7	0.938
5	219	5.5	355	51.230	35	98.02	3690	3694.7	0.999
6	219	5.5	355	53.025	49	99.64	3751	3802.3	0.987
7	133	4.5	345	28.704	7	87.92	1221	1276	0.956
8	133	4.5	345	40.80	53	101.3	1406	1447	0.972

Table 6. Further Comparisons of Analytical Results with FEM Results

No.	D /mm	T /mm	f_y /MPa	f_{ck} /MPa	t /day	f_{sc} /MPa	N_c /kN	N_f /kN	N_c/N_f
1	1000	12	345	18.641	3	41.95	32930	43497	0.757
2	1000	12	345	28.633	7	51.47	40402	49731	0.812
3	1000	12	345	35.836	14	58.33	45789	52161	0.878
4	1000	12	345	40.993	28	63.42	49781	54934	0.906
5	1000	18	345	18.641	3	53.41	41923	51250	0.818
6	1000	18	345	28.633	7	62.69	49213	57432	0.857
7	1000	18	345	35.836	14	69.39	54467	59979	0.908
8	1000	18	345	40.993	28	74.42	58422	63839	0.915
9	1000	24	345	18.641	3	64.70	50789	58000	0.876
10	1000	24	345	28.633	7	73.76	57898	64098	0.903
11	1000	24	345	35.836	14	80.28	63023	66483	0.948
12	1000	24	345	40.993	28	85.29	66955	70591	0.948
13	1000	30	345	18.641	3	75.86	59553	64129	0.929
14	1000	30	345	28.633	7	84.69	66484	70131	0.948
15	1000	30	345	35.836	14	91.06	71480	72343	0.988
16	1000	30	345	40.993	28	96.03	75382	76533	0.985
17	1000	36	345	18.641	3	86.87	68195	69795	0.977
18	1000	36	345	28.633	7	95.48	74950	75706	0.990
19	1000	36	345	35.836	14	101.68	79819	77777	1.026
20	1000	36	345	40.993	28	106.63	83702	81960	1.021

4. CONCLUSION

In the paper, an analytical solution was presented for composite strength of CFST columns considering the influence of concrete age of different hardening time. Bearing capacity experiments of CFST columns with different concrete age were conducted, and FM method was used to calculate the strength of CFST columns with different concrete aging time, steel ratio and concrete strength. Comparisons of composite strength between the formula, the experiment and the FE method results were made, which showed that the formula can predict the composite strength of CFST column well.

For the further work, it is needed to develop the formula of the stability property of CFST column considering the concrete age based on the one presented in this paper.

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