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Research on the Calculation Formula for the Ultimate Bearing Capacity of Axially Compressed Steel Tube UHPC Short Columns

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Abstract

In order to study the calculation formula for the ultimate bearing capacity of short columns of Ultra high performance concrete (UHPC) with axially compressed steel tubes, based on 100 sets of experimental results of UHPC short columns with axially compressed steel tubes in existing literature, the calculation formula for the ultimate bearing capacity of short columns was fitted and verified. The results indicate that the ultimate bearing capacity of steel tube UHPC short columns shows an overall upward trend with the increase of the hoop coefficient; The determination coefficient of the fitting formula for the ultimate bearing capacity of short columns is 0.986, and the correlation between the calculated results and the experimental results is good; The average ratio of the calculated value of the ultimate bearing capacity formula to the experimental value is about 1.0, with a small standard deviation and coefficient of variation. The calculated value of the formula is in good agreement with the experimental value. The formula obtained in this paper can be used for the calculation of the ultimate bearing capacity of UHPC short columns under axial compression.

Keywords

Ultra High Performance Concrete (UHPC); Steel Pipe; Ultimate Bearing Capacity.

1. Introduction

It is generally recognized that ultra-high performance concrete (UHPC) includes two types: reactive powder concrete (RPC) and ultra-high performance concrete with coarse aggregate (UHPC-CA) [1]. UHPC possesses ultra-high strength and durability, high toughness and deformation resistance, excellent workability, and outstanding environmental sustainability, making it better suited to meet the demands of high-rise, heavy-load, and long-span structures in civil and architectural engineering [2], and it remains a focal point in concrete research. Yang Shengfei [3] and others utilized solid waste materials such as iron tailings powder, silicon-manganese slag powder, and red mud to partially replace ordinary Portland cement as a binding material, collaboratively producing UHPC. When the water-to-binder ratio was 0.2 and the iron tailings powder content was 20%, the compressive strengths of UHPC at 3 d, 7 d, 14 d, 28 d, 56 d, and 112 d reached 76.3 MPa, 90.2 MPa, 101.7 MPa, 109.6 MPa, 114.5 MPa, and 120.4 MPa, respectively. Liu Shengbing [4] and others investigated the effects of steel fiber volume content on the mechanical and durability properties of UHPC through cube compressive strength tests, splitting tensile strength tests, freeze-thaw cycle tests, and sulfate corrosion resistance tests. The findings revealed: For test groups with varying coarse aggregate contents, when the steel fiber content was 1.5%, UHPC compressive strength increased by up to 25.6% compared to other dosages; for low coarse aggregate content groups (≤30%), UHPC splitting tensile strength continuously improved with increasing steel fiber content; in terms of durability, for the coarse aggregate-free test group, as steel fiber content increased, the strength loss rate and mass loss rate of UHPC gradually decreased, while freeze-thaw resistance progressively enhanced; for test groups with 15% and 30% coarse aggregate content, when steel fiber content increased from 0.5% to 1.5%, the 14-day compressive strength corrosion resistance coefficient gradually rose, indicating that UHPC's sulfate corrosion resistance gradually improved.

By combining steel pipes with UHPC, the steel pipes form circumferential constraints on the core UHPC. Under axial compression, UHPC is in a triaxial stress state, significantly improving compressive strength, ductility, and toughness. At the same time, the core UHPC provides support for the steel pipes, which can delay the local buckling of thin-walled steel pipes and fully utilize their excellent mechanical properties. This article is based on the experimental results of 100 sets of axially compressed steel tube UHPC short columns in existing literature, considering different influencing factors, to fit and verify the calculation formula for the ultimate bearing capacity of axially compressed steel tube UHPC short columns, in order to provide reference for the structural design and engineering application of steel tube UHPC columns.

2. Influencing Factors and Raw Data

Table 1. Test results of ultimate bearing capacity of short columns

Literature	No.	f_s/MPa	A_s/mm^2	f_c/MPa	A_c/mm^2	ξ	N_u/kN
Zhou Kaikai [7]	1	592.6	1900	111.3	8100	1.249	2051
	2	548.7	2256	111.3	7744	1.436	2182
	3	510.5	2604	111.3	7396	1.615	2270
	4	493.5	3600	111.3	6400	2.494	2657
	5	476.6	4816	111.3	5184	3.978	3135
	6	468.7	5904	111.3	4096	6.070	3587
	7	510.5	2604	90.3	7396	1.990	2169
	8	493.5	3600	90.3	6400	3.074	2572
	9	476.6	4816	90.3	5184	4.903	3063
	10	510.5	2604	81.4	7396	2.208	2046
	11	493.5	3600	81.4	6400	3.410	2468
	12	476.6	4816	81.4	5184	5.439	2976
Yang Yingxin [8]	13	383.1	1771	102.4	7390	0.897	1806
	14	383.1	1771	99.9	7390	0.919	1780
	15	383.1	1771	101.1	7390	0.908	1812
	16	383.1	1771	78.7	7390	1.167	1721
	17	383.1	1771	91.4	7390	1.005	1731
	18	383.1	1771	78.0	7390	1.177	1706
	19	383.1	1771	70.4	7390	1.304	1725
	20	351.0	2513	103.9	6648	1.277	1795
	21	351.0	2513	85.7	6648	1.548	1908
	22	351.0	2513	100.6	6648	1.319	1918
	23	351.0	2513	89.1	6648	1.489	1762
	24	351.0	2513	83.1	6648	1.597	1808
	25	351.0	2513	94.2	6648	1.409	1678
	26	351.0	2513	96.1	6648	1.381	1830
	27	366.2	3079	103.4	6082	1.793	2222
	28	366.2	3079	106.0	6082	1.749	2003
	29	366.2	3079	90.2	6082	2.055	2093
	30	366.2	3079	103.2	6082	1.796	2106
	31	366.2	3079	80.7	6082	2.297	2055
	32	366.2	3079	81.7	6082	2.269	1955
	33	366.2	3079	60.6	6082	3.059	2122
Wu Fanghong [9]	34	420.0	1548	112.1	8659	0.670	1928
	35	406.0	2036	112.1	8171	0.902	2082
	36	400.0	2664	112.1	7543	1.260	2265
	37	429.0	3267	112.1	6940	1.802	2507
	38	355.0	1548	112.1	8659	0.566	1596
	39	378.0	2036	112.1	8171	0.840	1950
	40	372.0	2664	112.1	7543	1.172	2282
	41	374.0	3267	112.1	6940	1.571	2375
	42	406.0	2036	87.8	8171	1.152	1768
	43	400.0	2664	87.8	7543	1.609	2115

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Continue Table 1

	44	406.0	2036	92.4	8171	1.095	1815
	45	400.0	2664	92.4	7543	1.529	1943
	46	420.0	1548	103.5	8659	0.725	1657
	47	406.0	2036	103.5	8171	0.977	1862
	48	400.0	2664	103.5	7543	1.365	2090
	49	429.0	3267	103.5	6940	1.951	2345
	50	355.0	1548	103.5	8659	0.613	1468
	51	378.0	2036	103.5	8171	0.910	1827
	52	372.0	2664	103.5	7543	1.269	2178
	53	374.0	3267	103.5	6940	1.701	2302
	54	406.0	2036	107.4	8171	0.942	1908
	55	406.0	2036	109.1	8171	0.927	1961
Feng Chen [10]	56	711.2	2501	106.3	29865	0.560	4953
	57	711.2	2501	106.3	29865	0.560	4953
	58	770.5	3713	106.3	28652	0.939	5907
	59	711.2	3720	102.9	66966	0.384	9536
	60	770.5	5542	96.8	65144	0.677	10576
	61	711.2	2336	105.5	20164	0.781	3788
	62	770.5	3456	102.7	19044	1.362	4617
	63	711.2	3136	106.7	36864	0.567	6163
	64	770.5	4656	102.9	35344	0.986	7222
	65	711.2	4736	102.7	85264	0.385	12124
	66	770.5	7056	105.5	82944	0.621	14184
Lin Yuhuang [11]	67	727.0	2372	131.0	37628	0.350	5828
	68	755.0	3121	131.0	36879	0.488	6641
	69	727.0	2372	84.0	37628	0.546	5086
	70	755.0	3121	84.0	36879	0.761	5788
	71	761.0	3900	84.0	36100	0.979	6057
	72	390.0	2364	84.0	37636	0.292	3876
	73	390.0	3121	84.0	36879	0.393	4437
	74	390.0	2364	125.0	37636	0.196	4990
	75	390.0	3121	125.0	36879	0.264	5736
	76	755.0	1529	125.0	8471	1.090	2239
	77	755.0	1927	131.0	13698	0.811	3206
	78	755.0	2325	131.0	20175	0.664	4547
	79	755.0	2723	131.0	27902	0.562	5548
	80	755.0	2723	103.0	27902	0.715	5099
	81	755.0	1529	103.0	8471	1.323	2207
	82	755.0	2723	118.0	27902	0.624	5570
	83	755.0	2723	139.0	27902	0.530	6039
	84	755.0	1529	134.0	8471	1.017	2425
Wang Qiuzhan [12]	85	703.0	1385	88.2	16286	0.678	3318
	86	703.0	1385	88.2	16286	0.678	3224
	87	703.0	1385	98.1	16286	0.610	3403
	88	703.0	1385	98.1	16286	0.610	3496
	89	703.0	1668	88.2	23779	0.559	4269
	90	703.0	1668	88.2	23779	0.559	4408
	91	703.0	1668	98.1	23779	0.503	4643
	92	703.0	1668	98.1	23779	0.503	4554
	93	628.6	3280	88.2	22167	1.055	6043
	94	628.6	3280	88.2	22167	1.055	6237
	95	628.6	3280	98.1	22167	0.948	6497
	96	628.6	3280	98.1	22167	0.948	6636
	97	628.6	4034	88.2	33979	0.846	7842
	98	628.6	4034	88.2	33979	0.846	7840
	99	628.6	4034	98.1	33979	0.761	8057
	100	628.6	4034	98.1	33979	0.761	8290

Note: N_u represents the ultimate bearing capacity test value of axially compressed steel tube UHPC short columns; ξ is the hoop coefficient, and the data ξ in the table ranges from 0.196 to 6.070.

The main factors affecting the axial compressive bearing capacity of steel tube UHPC short columns include the yield strength f_s of the steel tube, the cross-sectional area A_s of the steel tube, the axial compressive strength f_c of the UHPC, the core UHPC cross-sectional area A_c inside the steel tube, and the shape of the steel tube [6]. In order to obtain the calculation formula for the ultimate bearing capacity of axially compressed steel tube UHPC short columns, this paper collected 100 sets of experimental results from literature such as Zhou Kaikai [7], Yang Yingxin

[8], Wu Fanghong [9], Feng Chen [10], Lin Yuhuang [11], and Wang Qiuzhan [12] as raw data, as shown in Table 1. Among them, the steel pipes in references [7, 11] are square steel pipes, the steel pipes in references [8, 9, 12] are round steel pipes, and the first 5 groups in reference [10] use round steel pipes, while the last 6 groups use square steel pipes.

3. Fitting and Verification of Calculation Formula

3.1. Fitting of Calculation Formula

Research has shown that as the hoop coefficient ξ increases, the restraining effect of the steel pipe on the core UHPC increases, and the compressive strength and deformation capacity of the core UHPC improve. The ultimate bearing capacity N_u of axially compressed steel pipe UHPC short columns shows an increasing trend [13]. Plotting the data in Table 1 as a $N_u/(f_c A_c)$ - ξ scatter plot, it can be seen that $N_u/(f_c A_c)$ and ξ approximately exhibit a linear function relationship, therefore linear fitting should be performed. When fitting, referring to the method in reference [14], assuming the intercept of the linear function is 1, $N_u/(f_c A_c)=1+1.227\xi$ can be obtained, and the fitting result is shown in Fig. 1. As shown in the figure, the determination coefficient is 0.986 and the fitting effect is good. Therefore, the calculation formula for the ultimate bearing capacity of axially compressed steel tube UHPC short columns is shown in Equations (1-2).

$$N_u = f_c A_c (1 + 1.227\xi) \tag{1}$$

$$\xi = f_s A_s / f_c A_c \tag{2}$$

Where: N_u is the ultimate bearing capacity of axially compressed steel tube UHPC short columns; f_c is the design value of the axial compressive strength of UHPC; A_c is the cross-sectional area of the core UHPC inside the steel pipe; ξ is the hoop coefficient; f_s is the design value of compressive strength of steel; A_s is the cross-sectional area of the steel pipe.

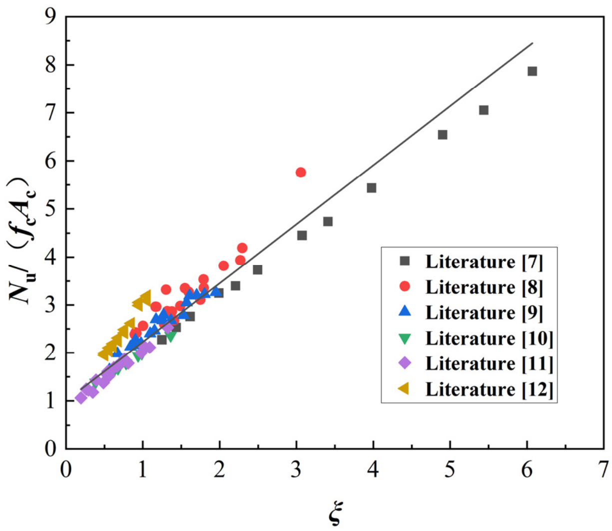

Fig 1. Fitting of the formula for calculating the ultimate bearing capacity of short columns

3.2. Verification of Calculation Formula

To verify the applicability of the fitting formula, the bearing capacity of 100 sets of experimental data in Table 1 was calculated based on Equations (1-2). The calculated value N_{u1} was compared and analyzed with the experimental value N_u, and the results are shown in Fig. 2. It can be seen that the average ratio of calculated values to experimental values is 0.976, the average error of the data is only 2.4%. The standard deviation is 0.119, and most ratios are in the range of 0.857-1.095. The coefficient of variation is 0.122, indicating a low degree of data dispersion. This result indicates that the calculated values are in good agreement with the experimental values, and Equations (1-2) can be used to calculate the ultimate bearing capacity of axially compressed steel tube UHPC short columns.

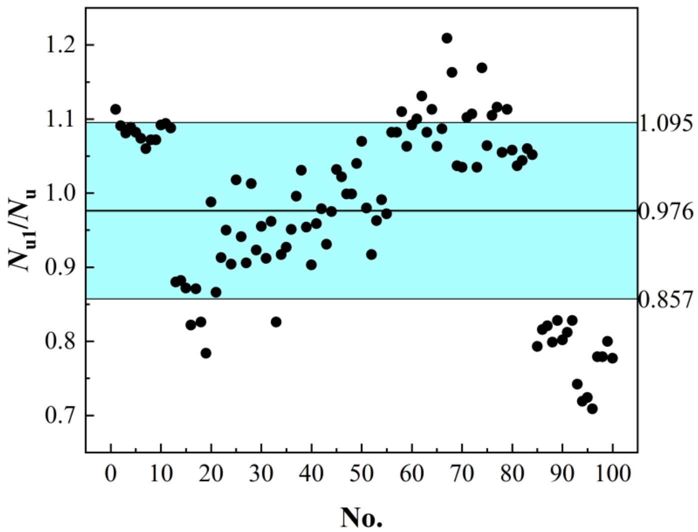

Fig 2. Comparison between calculated values and experimental values

4. Conclusion

(1) From the scatter plot of $N_u/(f_c A_c)$ - ξ, it can be seen that $N_u/(f_c A_c)$ is approximately a linear function of ξ, and the ultimate bearing capacity N_u of axially compressed steel tube UHPC short columns shows an overall upward trend with the increase of the hoop coefficient ξ.

(2) The calculation formula for the ultimate bearing capacity of axially compressed steel tube UHPC short columns is $N_u=f_c A_c$ (1+1.227 ξ), where $0.196 \leq \xi \leq 6.070$.

(3) The determination coefficient of the fitting formula for the ultimate bearing capacity of short columns is 0.986, indicating a good fitting effect.

(4) The average ratio of the calculated and experimental values of the ultimate bearing capacity of 100 sets of short columns is 0.976, with a standard deviation of 0.119 and a coefficient of variation of 0.122; The calculated values of the formula are in good agreement with the experimental values, and the formula obtained in this article can be used for the calculation of the ultimate bearing capacity of axially compressed steel tube UHPC columns.

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