

Finite Element Analysis on Axial Bearing Capacity of Square Double Skin Steel Stub Short Columns Filled with Recycled Concrete

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Abstract—Based on the compressive strength experiment of vitrified micro bubbles (VMB) recycled concrete double mixed diatomite calcined and fly ash, this paper adopts the finite element software ANSYS to analyze the impacts of different hollow ratio and VMB content on axial bearing capacity of square double skin steel stub short columns filled with recycled concrete in condition of 100% recycled coarse aggregate replacement ratio and 3% diatomite calcined content. The result shows that: Compressive strength of VMB recycled concrete increases with the increase of diatomite calcined content from 0 to 3%, when the content of diatomite calcined is 3%, compressive strength of the 130% VMB content test specimen can reach 32.45 MPa; When the hollow components reach ultimate bearing capacity, their axial displacement decrease by 5.6% compared to solid components, improving buckling capacity and ductility of components; When the VMB content is same, ultimate bearing capacity of hollow components compared to solid components increase by 2.5%; When the hollow ratio is same, ultimate bearing capacity of the 130% VMB content component compared with 0% content component only reduces by 3.5%; By means of the regression analysis of the component axial pressure data, we have exported bearing capacity of square double skin steel stub short columns filled with recycled concrete under axial compression.

Keywords—square double skin steel stub filled with recycled concrete; diatomite calcined; vitrified micro bubbles; axial bearing capacity; finite element analysis

I. INTRODUCTION

In recent years, vitrified micro bubbles is widely used as a new sort of environment-friendly and inorganic lightweight insulation materials, which can be used to make the VMB recycled concrete when it is added into the recycled concrete. Its strength and thermal insulation property can reach the ideal performance that is tested by the experiment[1]. Recycled concrete filled square steel tubes (CFST) is the structure style casting recycled concrete into the steel pipe, core concrete bears three directions force due to the restraint of the steel tube, improving the bearing performance and the recycled concrete engineering application value; Besides the same advantages with CFST, concrete filled double-skin steel tube (CFDST) could also expand cross section, with a higher bending rigidity lighter weight and better performance in earthquake resistant and fire resistant. Compared with those structural parts in style of SHS outer and SHS inner, SHS outer and CHS inner has better malleability[2-4].

Therefore, based on the compressive strength experiment of vitrified micro bubbles (VMB) recycled concrete double mixed diatomite calcined and fly ash, this paper adopts the finite element software ANSYS to analyze the impacts of different hollow ratio and VMB content on axial bearing capacity of square double skin steel stub short columns filled with recycled concrete, in condition of 100% recycled coarse aggregate replacement ratio and 3% diatomite calcined content, and we have exported bearing capacity of square double skin steel stub short columns filled with recycled concrete under axial compression.

II. GENERAL SITUATIONS OF EXPERIMENT

A. Experiment of VMB Recycled Concrete

Experiment uses 42.5 ordinary Portland cement; recycled coarse aggregate with a broken jaw crusher whose screening particle size is 5~20mm, bulk density is 1280kg/m³ and bibulous rate is 4.8%; sand fineness modulus is 2.9; fly ash uses the original ash from Yanji heating plant, basically reaching the level II for fly ash fineness requirements; Jilin Linjiang Tianyuan catalyst co.LTD., production of 325 mesh diatomite calcined, its performance parameters are shown in table 1; VMB produced by Linghai City Longyan Building Materials Factory, stacking density is 128kg/m³ whose performance parameters are shown in table 2; poly carboxylic acid high efficiency water reducing agent produced by Yenji Fangsheng Building Materials Company, water reducing rate is 25% or higher, which contains 0.8% of gas composition; mixing water is ordinary tap water.

After trial mixing, eventually water-binder ratio of VMB recycled concrete mixture ratio is 0.45, sand ratio is 30%. Results of each test block of experiment parameters and maintenance of indoor after curing 28d are shown in table 3.

Conclusions according to table 3: when the diatomite calcined content is same, increasing the VMB content, or when the dosage of VMB is same, increasing diatomite calcined content, the compressive strength of concrete both have a trend of increase; when diatomite calcined is 3% and the dosage of VMB is 130%, compressive strength of block is 32.45 MPa and its density is just 1942.45 kg/m³, compared with the ordinary concrete dry apparent density of 2000~2500 kg/m³, it can achieve reducing building self quality and improving anti-seismic performance.

TABLE I. PERFORMANCE OF DIATOMITE CALCINED AND VITRIFIED MICRO BUBBLES

Performance of diatomite calcined					Performance of vitrified micro bubbles				
Fe_2O_3 Content /%	SiO_2 Content /%	Specific surface area /(cm^2/g)	Ignition loss /%	Bulk density /(g/cm^3)	grain size /(mm)	Density /(kg/m^3)	thermal conductivity /[W/(m·K)]	Surface vitrified /%	Water absorption /%
≤1.5	≥92	600 thousand	≤0.5	≤0.42	0.5~1.5	50~200	0.0284~0.054	≥95	20~50

TABLE II. THE VMB RECYCLED CONCRETE EXPERIMENTAL PARAMETERS AND TEST RESULTS

Test specimen number	Material utilization amount/ (kg/m^3)								Compressive strength /MPa	Dry density / (kg/m^3)
	Cement	Fly ash	Diatomite calcined	Recycled coarse aggregate	Sand	VMB	water reducer	water		
BRC-0-3	349.11	93.5	14.2	1171.35	504	0	10.38	206	34.5	2118.05
BRC-100-3	458.18	122.6	18.4	1114.95	479.5	127.8	13.51	270	30.8	1969.35
BRC-100-2	464.3	122.6	12.31	1114.95	479.5	127.8	13.51	270	26.49	1965.43
BRC-100-0	476.49	122.6	0	1114.95	479.5	127.8	13.51	270	22.36	1909.12
BRC-130-3	458.19	122.6	18.4	1114.95	479.5	154	13.51	270	32.45	1942.45
BRC-130-2	464.25	122.6	12.31	1114.95	479.5	154	13.51	270	27.56	1910.28
BRC-130-0	476.49	122.6	0	1114.95	479.5	154	13.51	270	25.95	1923.42

Note: BRC-130-3,BRC represents VMB recycled concrete, 130 represents the VMB volume contains in the total volume is 130%,3represents that the diatomite calcined content is 3%, others can get by the parity of reasoning.

B. Design of test specimens

In order to study CFDST, length of the test specimen must be proper, length-width ratio of the test specimen is 3[5].Steel type is Q235,cross section form is shown in figure 1,main parameters of test specimens are shown in the table 3, $\chi = D_i / (B - 2t)$, $\xi = A_{so} f_y / (A_{co} f_{ck})$, in the formula, A_{so} is the outer steel pipe cross-sectional area, f_y is outer steel pipe yield strength, A_{co} is the area contained by the outer steel tube, f_{ck} is standard value of recycled concrete compressive strength.

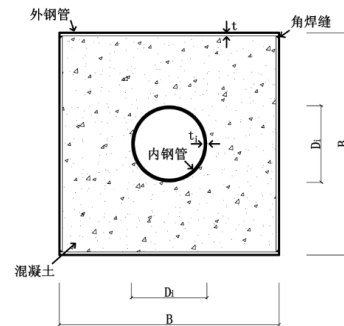


Figure 1. Cross section diagram of test Specimen

TABLE III. TEST SPECIMEN NUMBER AND MAIN PARAMETERS

Test specimen number	B×t×L /(mm ³)	D _i ×t _i /(mm ²)	Hollow ratio χ	Confining factor ξ	F_y /(MPa)	F_{cu} /(MPa)	N_{ANSYS} /(kN)
S-K1-0	180×2.5×540	—	0	0.5891	235	34.5	1110
S-K1-100	180×2.5×540	—	0	0.6599		30.8	1008
S-K1-130	180×2.5×540	—	0	0.6265		32.45	1061
S-K2-0	180×2.5×540	62×2.5	0.35	0.5891		34.5	1126
S-K2-100	180×2.5×540	62×2.5		0.6599		30.8	1041
S-K2-130	180×2.5×540	62×2.5		0.6265		32.45	1090

Note: All the specimens' diatomite calcined content of recycled concrete are 3%; K1 and K2 represent hollow ratios of test specimens are 0 and 0.35; 0、100、130 mean VMB content accounted for 0%、100% and 130% of the total concrete volume.

III. ESTABLISHMENT OF THE FINITE ELEMENT MODEL

A. The selection of element types

Steel uses the Solid45 element to simulate, $E_s=2.06 \times 10^5$ MPa, $V_s=0.3$; Concrete uses the Solid65 element to simulate, elastic modulus is calculated by recycled concrete elastic modulus formulas that is put forward by the reference [6], $V_t=0.2$.

$$E_c = \frac{10^5}{2.2 + 34.7 / f_{cu}} / (0.2811\delta + 1.065) \quad (1)$$

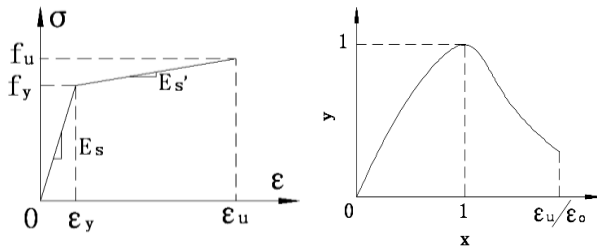


Figure 2. Material stress-strain relations

C. Modeling and Meshing

Regardless of slip between core concrete and steel tube, we add 15mm rigid plate in order to prevent the phenomenon of stress concentration on both ends of pillars. Quality of meshing directly affects the precision and speed of calculation, so hexahedron unit division side length of solid45 and solid65 are 15 mm. As shown in Fig .3.

D. Control of Convergence

1) Loading and boundary conditions

We add axial load on the upper plate, which generated by the rigid plate into uniformly distributed load on the model, at the same time we add x, y, z three directions of displacement constraints on the column bottom plate.

2) Concrete crush Settings

The open crack of concrete shear transfer coefficient and closed joint shear transfer coefficient are respectively set as 0.35 and 0.9 , axial tensile strength is 3 MPa, close the concrete crush option.

3) Nonlinear analysis options

Open the large deformation of static analysis and the automatic time step length, number of substeps is set as

In the formula: δ represents the replacement rate of recycled coarse aggregates, f_{cu} is the cube compressive strength of concrete.

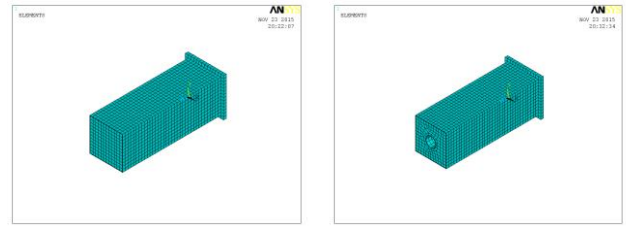
B. Constitutive relations of materials

1) Constitutive relation of steel

The steel uses dual linear kinematic hardening model (BKIN), which is shown in the figure 2 (a).

2) Constitutive relation of concrete

Literature research has shown that in the case of small hollow rate, mechanical properties of CFST and CFST are similar. Therefore, this paper uses the theory [7] that core recycled concrete stress-strain relationship model, as shown in figure 2 (b).



(a) CFST

(b) CFDST

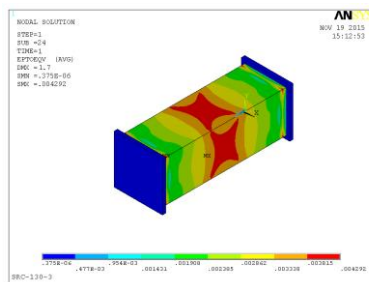
Figure 3. Finite element model

200 , maximum equilibrium iteration times is set as 40, the Newton - Laposen (N - R method) is used to solve and convergence tolerance is set as 0.05.

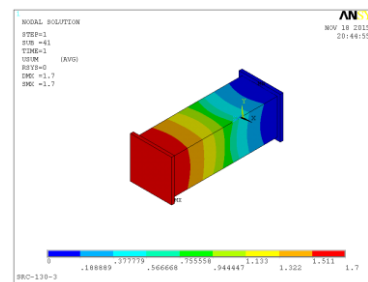
IV. CALCULATED RESULTS ANALYSIS OF FINITE ELEMENT

A. Strain and displacement analysis of test specimens

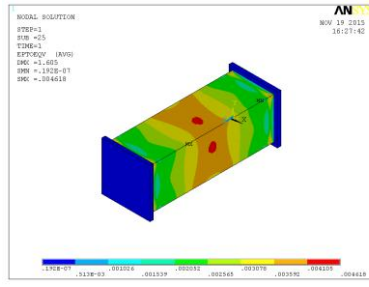
Fig .4. is the strain and displacement nephogram of test specimen S-K1-130 and S-K2-130 that have arrived the ultimate bearing capacity. As shown in Fig .4. (a) and (b), axial strain of the components corner in the end of load and constraint is apparently greater than other regions, especially the middle is apparently greater than its adjacent areas, local buckling occurs, axial displacement is 1.7mm; as shown in Fig .4. (c) and (d), hollow components appear the local buckling, but do not change apparently in the middle, which indicates the inner steel tube can prevent or delay local buckling of the component, axial displacement is 1.605mm that decreases by 5.6% compared with the solid components, setting of inner steel tube enhances the deformation capacity and improving the ductility.



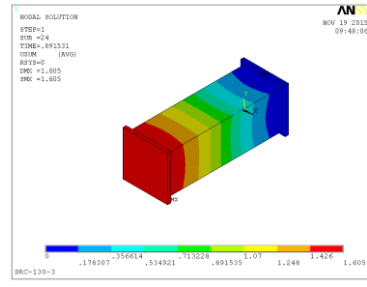
(a) S-K1-130 axial strain nephogram



(b) S-K1-130 Displace vector sum



(c) S-K2-130 axial strain nephogram



(d) S-K2-130 Displace vector sum

Figure 4. Component strain and displacement nephogram

B. Ultimate bearing capacity analysis of test specimens

At present, the research on CFST has achieved fruitful results and established regulations at home and abroad, this article uses CECS [8], AIJ [9], EC4[10] technical order and computational formula of ultimate bearing capacity put forward by Dong Jiangfeng[11] to analyze the ultimate

bearing capacity of three solid components, and based on the formulas we add inner steel tube bearing capacity as the ultimate bearing capacity computational formula of hollow components. The calculation results compared with the ANSYS finite element values are shown in table 4.

TABLE IV. COMPARISON BETWEEN ANSYS FINITE ELEMENT VALUES AND CALCULATION RESULTS

Number	ANSYS /kN	CECS /kN	AIJ /kN	EC4 /kN	Refer.[11] /kN	$\frac{N_{ANSYS}}{N_{CECS}}$	$\frac{N_{ANSYS}}{N_{AIJ}}$	$\frac{N_{ANSYS}}{N_{EC4}}$	$\frac{N_{ANSYS}}{N_{Refer.11}}$	Average value	Standard deviation
S-K1-0	1110	1131	1024	1269	1021	0.9814	1.0839	0.8045	1.0871	0.9892	0.1148
S-K1-100	1008	1040	947	1161	937	0.9692	1.0644	0.8070	1.0757	0.9791	0.1075
S-K1-130	1061	1092	991	1223	985	0.9716	1.0706	0.8053	1.0771	0.9812	0.1097
S-K2-0	1126	1170	1074	1295	1076	0.9623	1.0484	0.8308	1.0464	0.9720	0.0885
S-K2-100	1041	1089	1004	1198	1001	0.9559	1.0368	0.8355	1.0399	0.9670	0.0831
S-K2-130	1090	1135	1045	1254	1044	0.9594	1.0421	0.8325	1.0431	0.9693	0.0854

Results of ANSYS analysis are following: When the hollow ratio is same, the ultimate bearing capacity of 130% VMB component compared with content is 0% only reduces by 3.5%; When VMB content is same, though CFDST have reduced the amount of concrete, because of the inner steel tube, compared with solid components, their ultimate bearing capacity increase by 2.5%, which reducing weight and enhancing the anti-seismic performance of components; Finite element analysis results and the calculations of CECS, AIJ, EC4 and reference [11] are in good agreement. Through comparative analysis, we have found that adding inner steel tube bearing capacity on the axial compression bearing capacity formula can be used to calculate ultimate bearing capacity of hollow components.

For the thin-walled square steel tube concrete, they refer to the superimposed calculation formula of bearing capacity that considering the local buckling of the bearing capacity of steel tube and concrete after considering constraints[12], bearing capacity of square double skin steel stub short columns filled with recycled concrete is composed by bearing capacity of internal and external steel tube and core concrete. As shown in the formula 2.

$$N_u = F_s + kA_c f_{ck} + A_{si} f_{yi} \quad (2)$$

In the formula: A_c is section area of core concrete; A_{si} is section area of inner steel tube; f_{yi} is the yield strength of steel pipe; f_{ck} is standard value of recycled concrete compressive strength; F_s is the bearing capacity of the outer steel tube, B_e is equal to D_e in the square steel tube.

$$F_s = 2t f_y (B_e + D_e) \quad (3)$$

$$B_e = 7.4B \left\{ \frac{B}{t} \sqrt{\frac{f_y}{235}} \right\}^{-0.51} \quad (4)$$

Relationship between strength increase coefficient k of the core concrete and the effect of restraint coefficient ξ is linear[13]. So we did the regression analysis according to the axial pressure data of CFDST are shown in Figure 5.

Mathematical expression of strength increase coefficient k of the core concrete and the effect of restraint coefficient ξ is presented by the formula 5.

$$k = -0.019\xi + 1.0408 \quad (5)$$

Studies have shown that axial compressive properties of hollow and solid components are similar when the hollow rate is in a certain range, but inner steel tube is not binding. So we should subtract concrete bearing capacity of hollow part, if we calculate bearing capacity as a solid component.

$$\frac{A_{co} - A_c}{A_{co}} = \left[\frac{D_i}{B - 2t} \right]^2 = \chi^2 \quad (6)$$

In the formula: A_s is the outer steel pipe cross-sectional area, A_c is the area contained by the outer steel tube, χ is hollow rate.

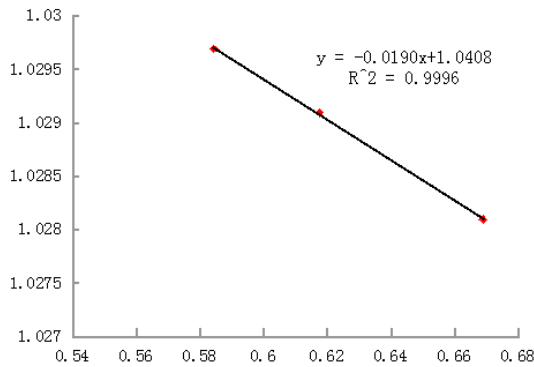


Figure 5. ξ -k relation curve charts

V. CONCLUSIONS

When the diatomite calcined content is same, with the increase of vitrified micro bubbles content, or when the vitrified micro bubbles content is same, with the increase of diatomite calcined content, compressive strength of recycled concrete shows a trend of increase; When diatomite calcined content is 3% and vitrified micro bubbles content is 130%, compressive strength of block can reach 32.45 MPa, and its density is just 1942.45 kg/m³;

Due to the inner steel tube setting of hollow components, when vitrified micro bubbles content is same, ultimate bearing capacity of hollow components compared to solid components increase by 2.5%, which reducing weight as well as improving the anti-seismic performance; their axial displacement compared with solid components decrease by 5.6% when they reach ultimate bearing capacity, which improving the buckling performance and increasing the ductility of components;

Maximum standard deviations of six CFDST of different hollow rates and vitrified micro bubbles content simulated values and calculated values are 0.1148 and 0.1097, which in good agreement;

Considering adverse effects of local buckling of big length-width ratio thin-walled SHS tube to ultimate bearing capacity, by means of the regression analysis data, we not only have found that relationship between strength increase coefficient k of the core concrete and the effect of restraint coefficient ξ is linear, but have exported bearing capacity of square double skin steel stub short

We can export bearing capacity of square double skin steel stub short columns filled with recycled concrete under axial compression when we introduce χ into formula 2.

$$N_u = F_s + (1 - \chi^2) k A_{co} f_{ck} + A_{si} f_{yi} \quad (7)$$

When χ is equal to zero, formula 7 can be used to calculate bearing capacity of square steel tube short columns filled with recycled concrete. Comparison results of simulated values and calculated values by formula 7 are shown in Fig. 6. We can see that the calculated values and simulated values are very close and in good agreement.

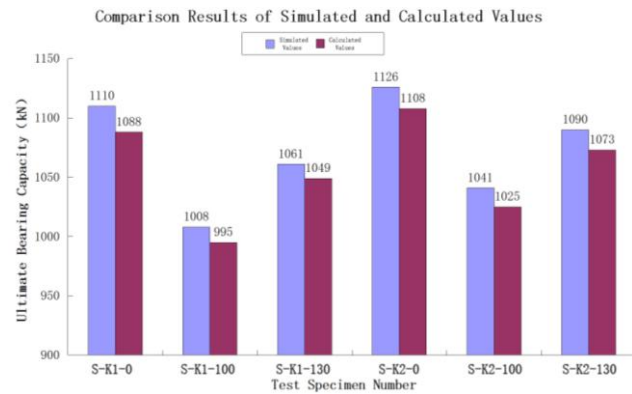


Figure 6. Comparison results of simulated and calculated values

columns filled with recycled concrete under axial compression.

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