Mechanical Properties of New Concrete-Filled Steel Tubular Support

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Abstract. Concrete-filled steel tubular (CFST) support has been gradually applied in the underground projects. According to the loading characteristics of underground projects supporting, the mechanical properties of CFST supports in roadway was analyzed by using theoretical analysis, laboratory tests and numerical simulations. The ultimate bearing capacity (UBC) of φ140×4.5mm CFST short column with the concrete strength of 26.8MPa was 1115.5kN by using the (UBC) formula deduced from the limit equilibrium theory, which was greater than the sum of that of the empty steel stub short column and that of the plain concrete short column. In the mechanical test of CFST support, the ultimate bearing capacity of the supports were 1.35 times larger than those of CFST short column because of the limitation of loading restrictive condition and the influence of the pole instability and eccentric compression on the whole CFST support. In the ABAQUS numerical simulation, the CFST support with the conditions of lateral confining loading constraint and horizontal restraint, the values of yield load and ultimate load of the CFST supports were two times larger than those of the short-column. Meanwhile, the CFST support had a large plastic deformation and its deformation rate could be up to 9%, so it can release the rock mass pressure energy by the deformation of the rock mass. And the support had a higher bearing capacity. So the CFST support was particularly suitable to support the roadway, especially the high ground stress deep roadway and extremely soft rock roadway.

Keywords: roadway support, CFST support, limit equilibrium theory, laboratory test, ABAQUS.

Concrete-filled steel tube (CFST) is one kind of composite member, which is composed of core concrete and outer steel tube [1-6]. Its working principle is that the confinement of steel tube makes core concrete in triaxial stress state, so the core concrete has a higher compressive strength, meanwhile, the core concrete and the steel tube bear axial pressure together, which combines the advantages of both the steel tube and the core concrete. The CFST structures have been applied in a variety of structural engineering field, such as CFST arch bridge.

CFST support is a new type of supports, which has been applied successfully to underground projects in large ground stress deep roadway and soft rock roadway for more than ten years [7-11]. According to the specific condition of roadway, cross-section shape of roadway is designed, and then the same-shaped steel tube

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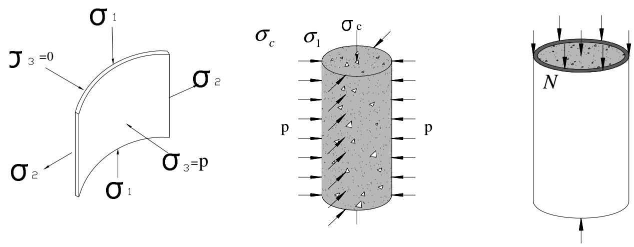
support is manufactured. The support can bear a higher load after pouring concrete into the steel tube. In the roadway, CFST support provides a strong supporting pressure, which is helpful to control surrounding rock deformation and maintain overall stability of roadway.

In this paper, the UBC ofφ140×4.5mm CFST short columns with the concrete strength of 26.8MPa is obtained by the UBC theoretical formula deduced from the limit equilibrium theory. The UBC and maximum deformation of φ140 × 4.5mm circular CFST support is analyzed by numeral simulation and the support loading test, which provide theory basis and technical support for the application of CFST supports in the underground engineering.

1 Mechanical Property of CFST Short Columns

Taking CFST short column under axial compression as an example, according to limit equilibrium theory and assumptions of the limit (yield) conditions of steel and core concrete, its ultimate carrying capacity is obtained[1,12-14], as shown in fig.1.



(a) Steel tube (b) Core concrete (c) CFST

Fig. 1 Force distribution diagrams of steel tube and core concrete

$$N_0=A_cf_c(1+2\theta) \tag{1}$$

$$N_0=A_cf_c(1+\sqrt{\theta}+1.1\theta) \tag{2}$$

Where N_0 is external load, σ_c is compressive strength of concrete core, σ_1, σ_2 are longitudinal stress and hoop stress of steel tube, respectively, p is lateral pressure between the steel and concrete.

The confining index θ is given by the following equation,

$$\theta = A_sf_s/A_cf_c \tag{3}$$

Where A_s, f_s are cross-sectional area and yield strength of steel tube, respectively, and A_c, f_c are the cross section area and compressive strength of core concrete, respectively, θ stands for hoop constraint degree of steel tube on core concrete.

According to the above theory formula(1), for the φ140×4.5 mm seamless steel tube and the concrete grade of C40, the UBC of plain concrete short column, hollow circular steel tube short column, CFST short column are obtained, as shown in fig.2. The UBC of CFST short column is 1115.5kN, which is greater than the sum of that of the empty steel stub short column and that of plain concrete short column.

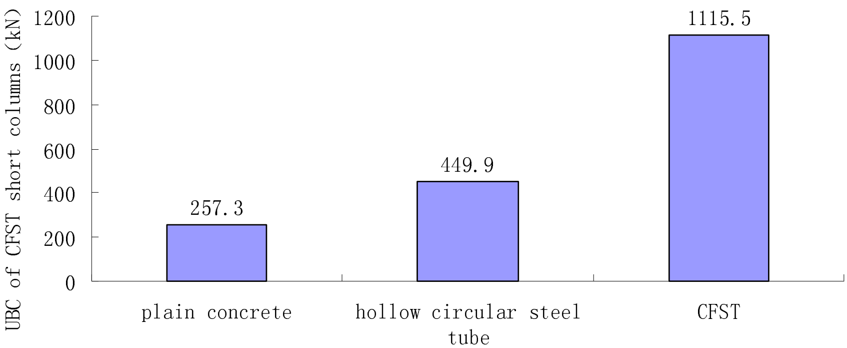


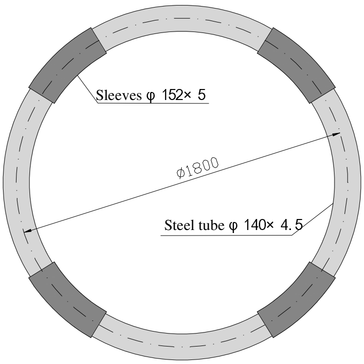
Fig. 2 UBC of short columns

2 Mechanical Properties Test of CFST Support

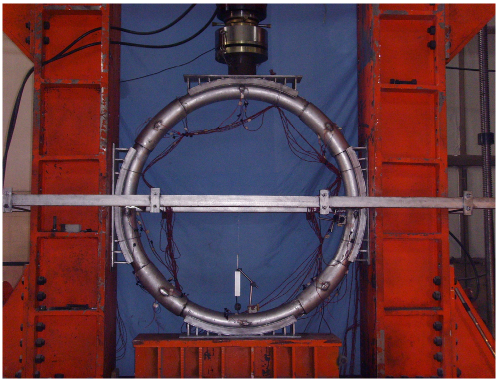
2.1 Experimental Model of CFST Support

The circular CFST support specimen is composed of four CFST parts, as shown in fig.3(a), CFST support usesφ140 × 4.5mm seamless steel tube with the length of 1413mm and 400mm length sleeves of φ152 × 5mm seamless steel tube. The diameter of CFST supports is 1800mm.

The bearing plate is set on each CFST parts. The test load device structure is shown in fig.3(b), and adopts monotonic step loading and monitor the vertical and horizontal relative displacement.



(a) CFST support structure



(b) loading device

Fig. 3 CFST support mechanical test

2.2 Stability Calculation of Bearing Capacity and Support Pressure of CFST Support

The stability bearing capacity of CFST support is given by,

$$N_u = \varphi_l N_0 \tag{4}$$

Where, φ_l is the reduction coefficient of slenderness, $\varphi_l = 1 - 0.115\sqrt{l_0 / D - 4}$.

So, the stability bearing capacity of CFST support was obtained: $N_u = \varphi_l N_0 = 981.6\text{kN}$. l_0=706.7mm, D=140mm, $N_0 = 1115.5\text{kN}$.

The CFST support can be simplified into semi-circular CFST Support (fig.6)

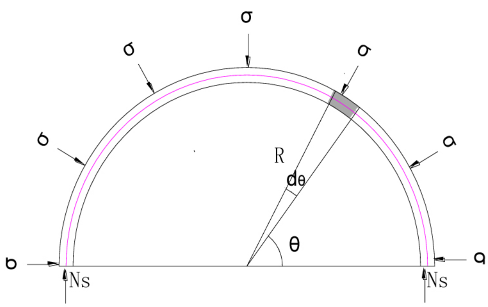


Fig. 4 Support pressure of CFST support diagram

$$s \cdot \int_0^{180} \sin\theta \cdot \sigma \cdot R \cdot d\theta = 2 \cdot N_{\mathrm{u}} \tag{5}$$

Where, N_u is the stability bearing capacity of CFST support and equal to 981.6kN, s is row spacing of CFST support and equal to 0.8 mm, R is the radius of CFST support and equal to 0.9 m, σ is support pressure of CFST support.

Then the supporting pressure can be calculated by using the equation (2). Its value is $1.36MPa$.

2.3 Test Results and Analysis

The relationship between the applied load and relative displacement of the CFST support is shown in fig.5. With the increase of the applied load on the CFST support, the support enters into structural deformation state, elastic deformation state and plastic deformation state in sequence(tab.1)

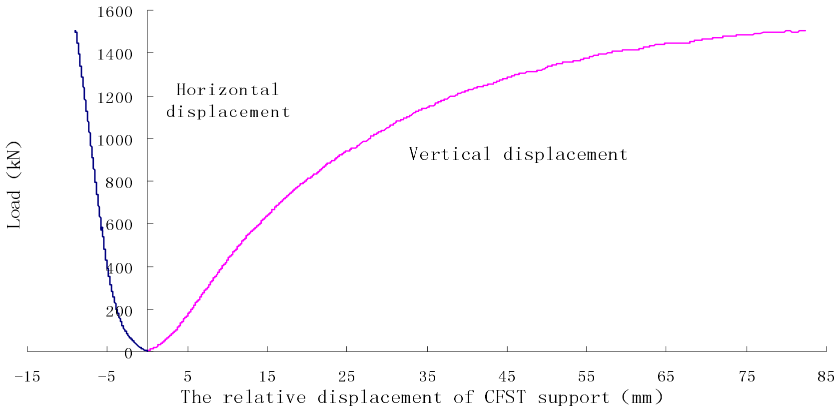
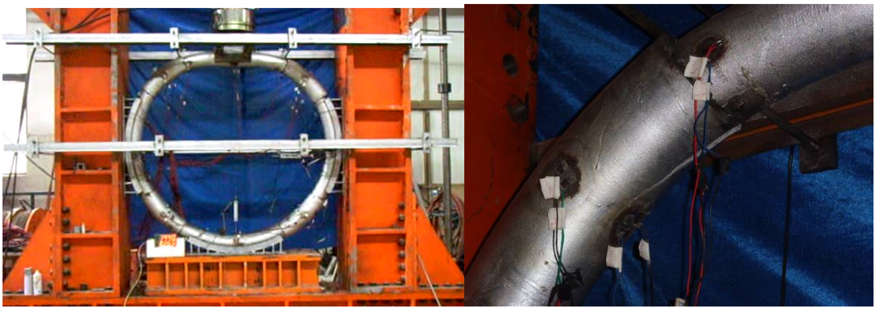


Fig. 5 Load-displacement curves of CFST support specimen

Table 1 The UBC and relative displacements during CSFT support deformation stage

CSFT short columns deformation stage	**Stage Ultimate loads (kN)**	**Vertical relative displacement (mm)**	**Horizontal relative displacement (mm)**
Structural deformation	137.6	4.4	-3.3
Elastic deformation	1168.4	36.5	-7.8
Plasticity-harden	1504.1	80.4	-8.9



(a) overall deformation (b)local destruction

Fig. 6 Failure model of tested support

The test stops, because the upper left sleeve cracks and the cross section of steel tube becomes larger significantly(fig.6) The ultimate load of CFST support is 1504.1kN, namely, the calculated value of supporting pressure of the CFST support is 1.04MPa. The maximum value of the vertical relative displacement of CFST support specimen is 80.4mm, which is 4.47% of the diameter of CFST specimen.

3 Numerical Simulations on CFST Support in Roadway

3.1 Model of CFST Support and Surrounding Rock of Roadway

The size of roadway surrounding rock model is 10m×10m×0.8m with circular cross section. CFST support uses φ140 × 4.5mm seamless steel tubes with the diameter of 1800mm, and the concrete grade of the core concrete that is simulated by using concrete plastic damage model. Steel tube used in this study is Q235 steel, which is simulated by using elastic-plastic model, has the properties of elastic modulus of 206GPa, Poisson's ratio of 0.3, and a density of 7800kg/m^3. Its plastic stress-strain curve is shown in fig.7. Roadway surrounding rock employs Mohr- Coulomb model (tab.2), The parameters of concrete are shown in tab. 3[15-19].

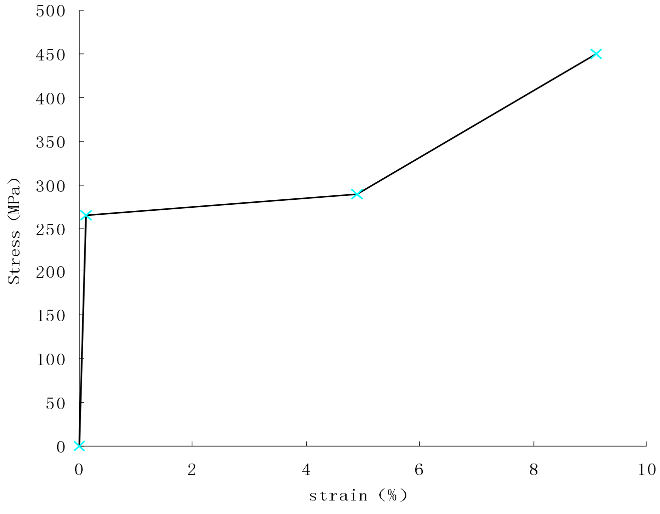


Fig. 7 Stress - strain curve of steel

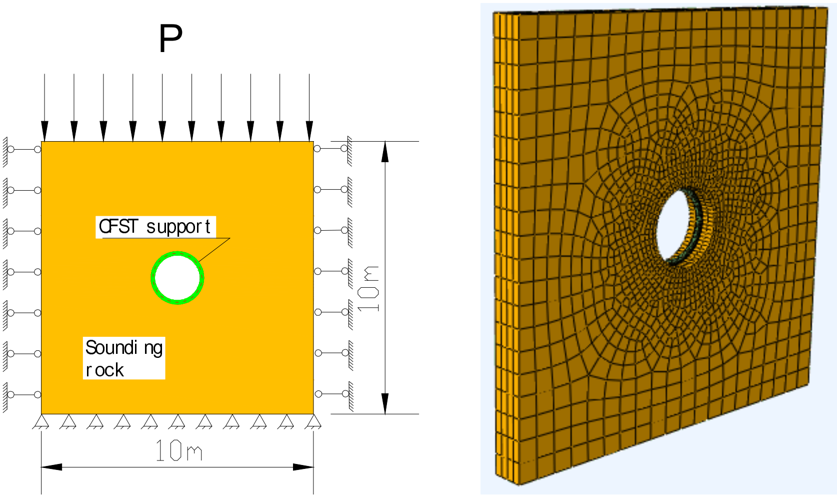
Table 2 Parameters of surrounding rock

Strata	Density kg • m^{-3}	Elastic modulus GPa	Poisson ratio	Cohesion MPa	Internal friction angle (°)	Tensile strength MPa
Sounding rock	2541	1.25	0.3	1.5	30	4.0

Table 3 Parameters of concrete damage plasticity model

Density (kg • m^{-3})	Elastic modulus MPa	Poisson ratio	Dilation angle ψ (°)	Flow potential eccentricity, ξ	Ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress σ_{b0}/σ_{c0}	Ratio of the second stress invariant on the tensile meridian K_c	Viscosity parameter μ
2400	39.2	0.2	40	0.1	1.225	0.66667	0.0005

Concrete is filled into steel tube completely. Assuming that there is no relative sliding between steel tube and core concrete during the loading process, contact surface adopts tie command in constraint. Fixed boundary for the bottom of the model, limited the horizontal direction displacement for lateral four surfaces, gradually applied pressure on the top model up to the destruction of CFST support, under a large-deformation mechanical model, are used. Surrounding rock, steel tube and core concrete are molded by eight-node hexahedral reduced integration linear solid elements form three-dimensional (C3D8R). Mechanical model and mesh of all the related materials are shown in fig.8 (a) and fig. 8(b) respectively.



(a) (b)

Fig. 8 Mechanical model of CFST support in roadway (a) and its mesh (b)

3.2 Simulation Results and Analysis

The load-displacement curves of CFST support is shown in fig.9. With the increase of applied load, support enters into the structural deformation, elastic deformation, plastic deformation and plastic hardening, respectively, as shown in table 4.

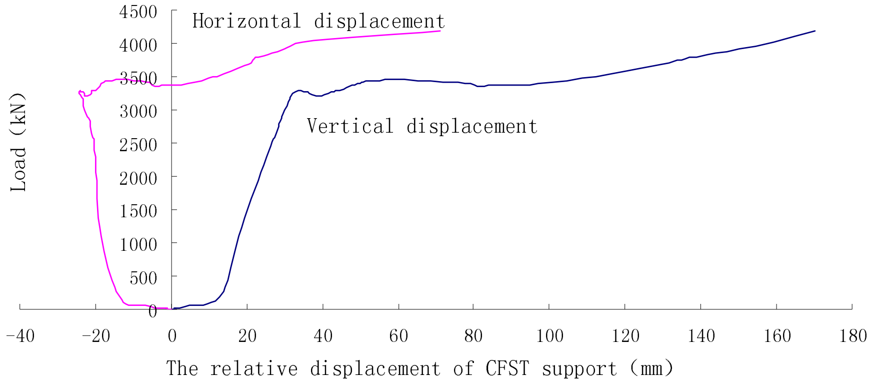


Fig. 9 Load-displacement curve of support

Table 4 The UBC and relative displacements in different deformation stages of CSFT support

CSFT support deformation stage	**Stage ultimate load（kN）**	**Vertical relative displacement（mm）**	**Horizontal relative displacement（mm）**
Structural deformation	279.3	14.1	-12.1
Elastic deformation	3286.3	33.5	-24.3
Elastic-plastic deformation	3474.6	108.5	8.2
Plasticity-harden deformation	4194.2	161.3	34.5

Steel tube of two horizontal sides of CFST supports reaches to the stress limit and damages, as shown in fig.10. The ultimate load of CSFT supports is 4194.2kN, its support pressure is 2.91MPa, the maximum deformation is 8.9% of the support diameter, and the outer diameter of steel tube increased from 140mm to 149.5mm. The cross-sectional area of the support arcs is increased significantly to further improve the UBC of CFST.

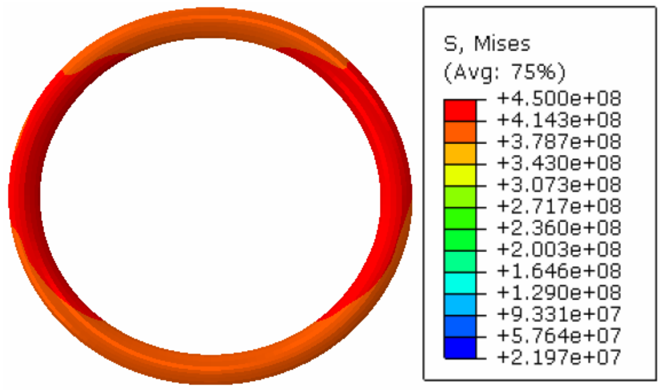


Fig. 10 MISE stress contour of CFST support destruction

4 Conclusions

(1) The UBC theoretical formula of CFST short column was deduced from the limit equilibrium theory. The UBC of φ140×4.5mm CFST short column was 1115kN, which was greater than the sum of that of the empty steel stub short column and that of the plain concrete short column.

(2) In the CFST support load test, the effects including the limitation of loading restrictive condition, the influence of the pole instability and eccentric compression on the whole CFST support, and non-uniform distribution of stress on different portions of the support, leaded to the crack of the top left corner sleeves. So the value of ultimate load of test support was 1.35 times that of CFST short column.

(3) In ABAQUS numerical simulation, circular equal strength CFST support in roadway support was under equal application of pressure and lateral restraint, which reduces the effect of pole instability. The modeled support yield and ultimate loads were twice times more than that of short column, while the modeled support could bear the plastic large deformation. Its deformation rate was nearly 9%.

(4) CFST support had a higher bearing capacity in the roadway support, and itself had the mechanical properties of bearing large deformation to release the sounding rock pressure. So CFST supports were particularly suitable to be applied to roadway support in high ground stress deep roadway or broken soft rock roadway.

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