



# Study on Bearing Mechanism and Coupling Mechanism of Steel Arch-concrete Composite Structure of Initial Support System of Large Section Tunnel

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**Abstract** Fully utilizing and developing underground space is an important direction of future world development. In order to meet the increasing traffic demand, there are more and more super-large section tunnel projects such as two-way eight-lane tunnel. In the initial support system of NATM, “steel arch + concrete shotcrete” is widely used in engineering as one of the most common forms of support. But at present, in the study of supporting system, most researches are based on mechanical analysis of single steel arch, and few of them consider the spatial combination of multi-arch and the influence of concrete shotcrete. Therefore, in order to grasp the spatial combination effect of multi-arch and the influence of concrete shotcrete layer on the bearing mechanism of initial support system, and to establish the analysis and calculation model of initial support system, this paper carries out numerical tests on the mechanical characteristics of three composite steel arch + concrete

shotcrete initial support system, and clarifies the spatial combination effect of multi-arch and the effect of concrete shotcrete on initial support. Based on the bearing capacity of the initial support system, the influence of concrete shotcrete strength, arch spacing and longitudinal connection spacing on the mechanical properties of the initial support system is comprehensively analyzed. The research results can provide theoretical basis for the design and application of related engineering.

**Keywords** Concrete shotcrete · Spatial combinational arch · Initial support system · Coupling bearing mechanism

## 1 Introduction

Fully utilizing and developing underground space is an important direction of future world development (Sharifzadeh et al. 2013; Li et al. 2018; Abdullah et al. 2016; Ding et al. 2017). In order to meet the increasing traffic demand, there are more and more super-large section tunnel projects such as two-way eight-lane tunnel.

However, in the process of excavation and support of large section tunnel, due to its large cross-section size, low flat rate, complex construction procedures, surrounding rock disturbance and others, problems such as inadequate initial support strength and the loss

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of bearing capacity arise frequently, and thus lead to instability of the excavating face, tunnel collapse and other disasters.

Nowadays, the “NATM” construction method is widely used in tunnel engineering. Among the many initial supporting structures, the “steel arch + concrete shotcrete” support has good tightness with surrounding rock, so it is widely used as a most common form of support in tunneling.

The arch and longitudinal connection play the role of “skeleton” in the initial support, which can effectively prevent the cracking and falling of concrete shotcrete layer, and greatly improve the bearing strength of initial support. At the same time, it has the characteristics of deformation coordination and joint bearing between concrete shotcrete and arch (Shu-chen et al. 2014; Bin et al. 2017).

Therefore, it is inappropriate to divide the arch structure and the concrete shotcrete into two parts and study their load-bearing laws independently. This paper will further study the mechanical characteristics of the initial support and its controlling effect on the deformation of the surrounding rock based on the Letuan tunnel (Fig. 1).

In this paper, a typical two-way eight Lane large section tunnel—LeTuan tunnel in eastern China is taken as the engineering background. The tunnel project is large in scale with 2010 m in length, 19.1 m

in width and 9.9 m in height. Most regions of the tunnel are located in limestone areas, where complex geological conditions such as shallow-buried bias, fault fracture zone and karst cave exist (Baltay and Gjelsvik 1990).

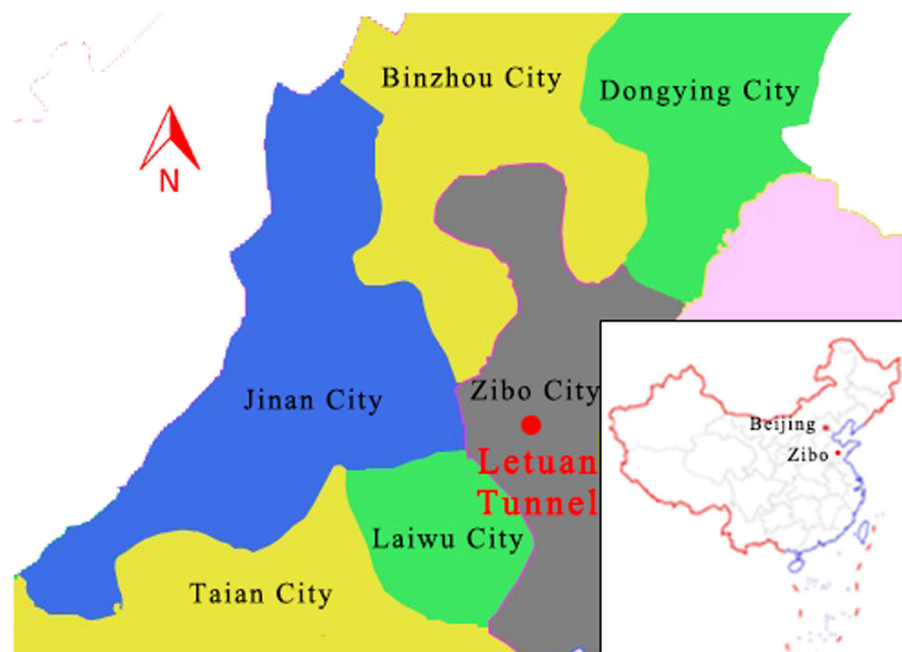
In this paper, a tunnel excavation and support model is established; a series of comparative working conditions with different concrete shotcrete strength, different arch spacing and different longitudinal connection spacing are set; the capacity characteristics of initial support under different working conditions and the controlling effect on tunnel deformation are analyzed, and mechanical characteristics and deformation control of initial support for large section tunnel are cleared.

## 2 Numerical Modelling

### 2.1 Model Information

According to the field working condition of Letuan Tunnel of Binlai highway, a calculation model is established according to the physical and mechanical properties of rock and ground stress distribution provided by the engineering geological investigation report. The size of the model is 100 m in height, 100 m in width and 48 m in depth. The tunnel depth is 48 m,

**Fig. 1** The location of Letuan tunnel



and the model does not apply compensation stress. The upper boundary is directly established to the surface. The three directions of X, Y and Z at the bottom of the model, the X directions on both sides, and the Z direction in posterior direction are constrained. The numerical model is shown in Fig. 2.

### 2.2 Material Constitutive Relation

According to the engineering geological investigation report, the Mohr–Coulomb criterion is adopted for the rock and soil mass, and the specific mechanical parameters are shown in Table 1.

The elastoplastic constitutive model is adopted for the arch, and the elastic modulus and the poisson ratio are 206 GPa and 0.3 respectively. A simplified quadratic plastic flow model is used to describe the stress–strain relationship of the section steel. The relationship curve is divided into 4 sections, which are elastic section, yield section, strengthening section and secondary yield section. The model can well reflect the yielding and hardening phenomena of steel during monotonic loading. The stress–strain relationship can be calculated according to Formula 1.

$$\sigma = \begin{cases} E_s \varepsilon & \varepsilon \leq \varepsilon_y \\ f_y & \varepsilon_y < \varepsilon \leq \varepsilon_{uy} \\ E_t (\varepsilon - \varepsilon_y) + f_y & \varepsilon_{uy} < \varepsilon \leq \varepsilon_u \\ f_u & \varepsilon \geq \varepsilon_u \end{cases} \quad (1)$$

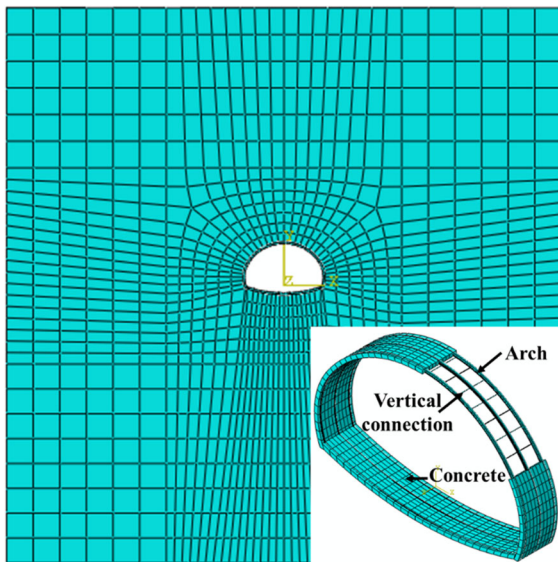


Fig. 2 Numerical model for tunnel support

$E_s$  is the elastic modulus of steel;  $f_y$  is the yield strength of steel;  $\varepsilon_y$  is the yield strain of steel;  $\varepsilon_{uy}$  is the initial strain of steel strengthening section and its value is  $10\varepsilon_y$ ;  $E_t$  is the strengthening modulus of steel;  $f_u$  is the ultimate strength of steel;  $\varepsilon_u$  is the ultimate strain of steel.

The plastic damage model is adopted for concrete. The mathematical expression of tensile stress–strain relationship of concrete is (Jumin et al. 1993; Jianjing et al. 2005; Jianguo and Yuhang 2013):

$$y = \frac{x}{0.31\sigma_p^2(x-1)^{1.7} + x} \quad (2)$$

$y = \sigma/\sigma_p$ ;  $x = \varepsilon/\varepsilon_p$ ;  $\sigma_p$  and  $\varepsilon_p$  are peak tensile stress and peak peak tensile strain respectively;  $\sigma_p = 0.26(1.25f'_c)^{2/3}$ ;  $\varepsilon_p = \sigma_p/E_c$ ;  $E_c$  is the elastic modulus of concrete, and the value is calculated according to  $E_c = 4000\sqrt{f'_c}$ ;  $f'_c$  is the compressive strength of concrete.

In compression, the stress–strain relationship of concrete is recommended by Attard and Setunge 1996.

Eight-node reduced integral three-dimensional solid element (C3D8R) is used for surrounding rock, arch, longitudinal connection and concrete shotcrete. Tie bind is applied between surrounding rock and arch, as so as between arch and longitudinal connection. Deformation coordination exists between arch, longitudinal connection and concrete shotcrete, and embedded region contact is adopted. The interface contact mode is divided into normal contact and tangent contact. Hard contact is adopted for normal contact. Coulomb criterion is adopted for tangent contact to simulate the friction, and elastic sliding deformation is used to calculate the interface slip. The mathematical expression of shear stress transfer is as follows:

$$\tau = \mu p \geq \tau_b \quad (3)$$

$\tau$ —Shear stress;

$\mu$ —Friction coefficient, Baltay and Gjelsvik (1990) suggested that  $F$  should generally be 0.2–0.6, while Schneider (1998) suggested that  $F$  should be 0.25, and the interfacial friction coefficient  $f$  in this model should be 0.6.

$p$ —Normal pressure;

$\tau_b$ —Average bond stress between steel and concrete shotcrete.

**Table 1** Mechanical parameters of surrounding rock

Surrounding rock grade	Density $\rho$ (kg/m <sup>3</sup> )	Elastic modulus $E$ (GPa)	Poisson ratio $\nu$	Cohesion $c$ (MPa)	Internal friction angle $\varphi$ (°)
IV	2683	3.5	0.29	45	29

### 2.3 Test Scheme

Firstly, the effect of different strength concrete shotcrete on the deformation control of tunnel is studied. Secondly, the study on the bearing capacity of initial support with different strength of concrete shotcrete, different arch spacing and different longitudinal connection spacing is carried out. Concrete shotcrete strength design into five levels with C20, C25, C30, C35 and C40, arch spacing design into six levels with 0.4 m, 0.6 m, 0.8 m, 1.0 m, 1.2 m and 1.4 m, longitudinal connection spacing design into five levels with 0.5 m, 1.0 m, 1.5 m, 2.0 m and 2.5 m. A series of comparative conditions are set, the specific factors are shown in Table 2.

## 3 Numerical Results Analysis

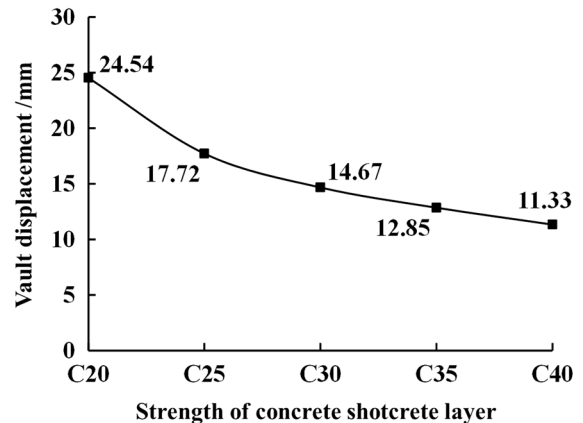
### 3.1 The Influence of Concrete Shotcrete Strength

#### 3.1.1 Deformation Control Effect of Tunnel

The crown settlement of tunnel with different strength of concrete shotcrete is compared and analyzed, and the control effect of concrete shotcrete strength on tunnel deformation is obtained.

As shown in Fig. 3,

- (1) The vault settlement decreases as the concrete shotcrete strength increases. When the concrete shotcrete strength is C20, the vault settlement is

**Fig. 3** Effect of concrete shotcrete strength on tunnel deformation

close to the specification value of tunnel construction, and this indicates that the control effect on the deformation of the large section tunnel is weak; when the concrete shotcrete strength is C25, the vault settlement does not exceed 1/2 of the specification value, which indicates that it has obvious control effect on the deformation of the large section tunnel.

- (2) The crown settlement differences between different concrete shotcrete are 6.82 mm, 3.05 mm, 1.82 mm and 1.52 mm respectively, and this difference decreases gradually with the increase of concrete shotcrete strength. When the concrete shotcrete strength exceeds C30, the

**Table 2** Specific factors in numerical experiments

Serial number	Strength grade of concrete shotcrete	Arch spacing (m)	Longitudinal connection spacing (m)
1	C20	0.4	0.5
2	C25	0.6	1.0
3	C30	0.8	1.5
4	C35	1.0	2.0
5	C40	1.2	2.5
6	–	1.4	–

control effect of concrete shotcrete strength on the deformation of large section tunnel cannot be exerted, and the strength utilization ratio is low.

### 3.1.2 Influence Law of Initial Support Mechanical Properties

As shown in Fig. 4:

- (1) The concrete shotcrete has obvious influence on the arch stress distribution. With the increase of concrete shotcrete strength, the maximum stress of arch decreases slightly. The maximum stresses of arch under C25 and C40 concrete shotcrete conditions are 579.00 MPa and 548.38 MPa respectively, which decreases only 5.58%.
- (2) The stress of concrete shotcrete with different strength presents “three high and two low” strip-like distribution, the arch area shows high stress zone, and the area between adjacent arches shows low stress zone. It is known that the arch has obvious skeleton effect in the initial support.
- (3) The maximum stress is concentrated at the arch foot, which is the key point of the whole initial support system to bear external load. The arch foot should be paid attention to in situ construction and corresponding auxiliary measures should be taken.

## 3.2 The Coupling Bearing Effect of Concrete Shotcrete Strength and Arch Spacing

### 3.2.1 Tunnel Deformation Control Effect

As shown in Fig. 5:

- (1) With the increase of the arch spacing, the vault settlement differences decrease gradually under different strength concrete shotcrete. But when the arch spacing is 1.2 m, the vault settlement difference is too large, this indicates that the skeleton effect of the arch combination structure on the concrete shotcrete is reduced, and the control effect of the initial support on the deformation of the tunnel is getting worse.

- (2) With the increase of concrete shotcrete strength, the crown settlement difference under different arch spacing conditions increases gradually, which shows that the load sharing effect of concrete shotcrete is getting smaller, and its effect on tunnel deformation control is also getting smaller.

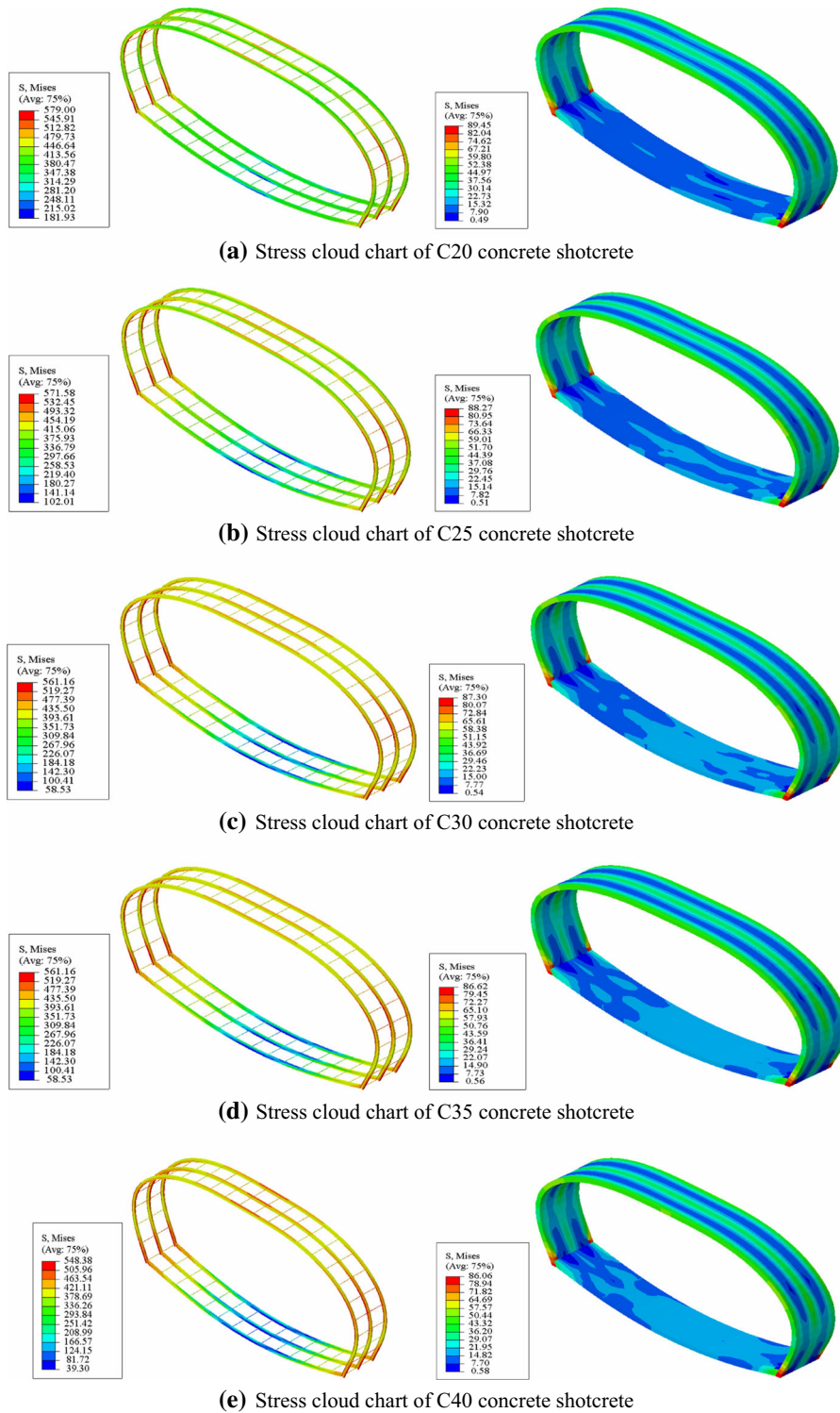
### 3.2.2 Stress Distribution Law of Initial Supporting Members Under Coupling Effect

Figure 6 is the representative stress maps of initial support system with different concrete shotcrete strength and arch spacing in numerical test. The analysis is as follows:

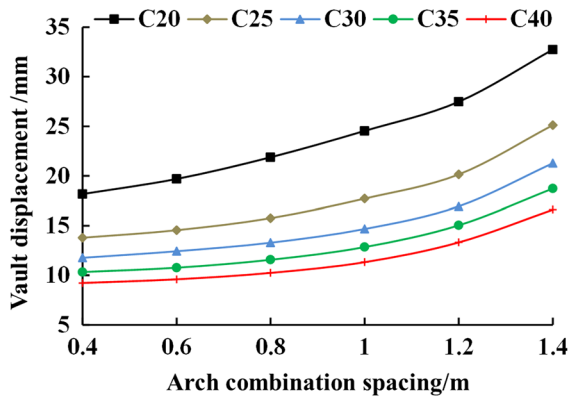
As shown in Fig. 6,

- (1) The influence of concrete shotcrete strength on stress distribution is obvious. The stress distribution of the arch is uniform, and the stress concentration phenomenon is obvious. Stress concentration occurs at the outer flange of vault, the inner flange of arch waist and the arch foot. With the increase of concrete shotcrete strength, the stress concentration area of the vault decreases gradually, the stress concentration area of the arch waist and the arch foot enlarges gradually, and the stress difference in the section of the stress concentration area increases gradually. The maximum stress decreases slightly with the increase of concrete shotcrete strength. It can be seen that the concrete shotcrete has obvious effect on the adjustment of stress distribution trend of arch, but the effect on the adjustment of stress value in stress concentration area is poor.
- (2) The stress distribution of concrete shotcrete presents obvious stress band distribution, which indicates that with the increase of the arch spacing, the supporting effect on the skeleton of concrete shotcrete is no longer cohesive. This results in the gradual separation of stress influence range, which leads the stress differentiation of concrete shotcrete into “three high and two low” state which is similar to the arch. At the same time, the strip stress distribution phenomenon weakens or even disappears at the vault and arch waist, which indicates that the skeleton support effect of the arch on the





**Fig. 4** Stress nephogram of initial support structure with different concrete shotcrete strength



**Fig. 5** Effect of coupling bear between concrete shotcrete strength and arch spacing on tunnel deformation

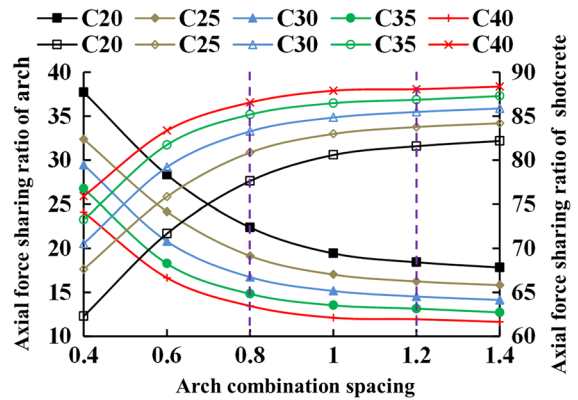
concrete shotcrete basically disappears, and the influence distance of the skeleton support effect is less than 1.0 m of the arch spacing.

### 3.2.3 Load Sharing Ratio of Initial Supporting Members Under Coupling Effect

According to the numerical test results, the axial force and bending moment sharing ratio of concrete shotcrete and arch under the coupling action of different strength shotcrete layer and arch spacing is drawn.

#### (1) Axial force sharing ratio

As shown in Fig. 7, the axial force sharing ratio difference of the arch decreases with the increase of

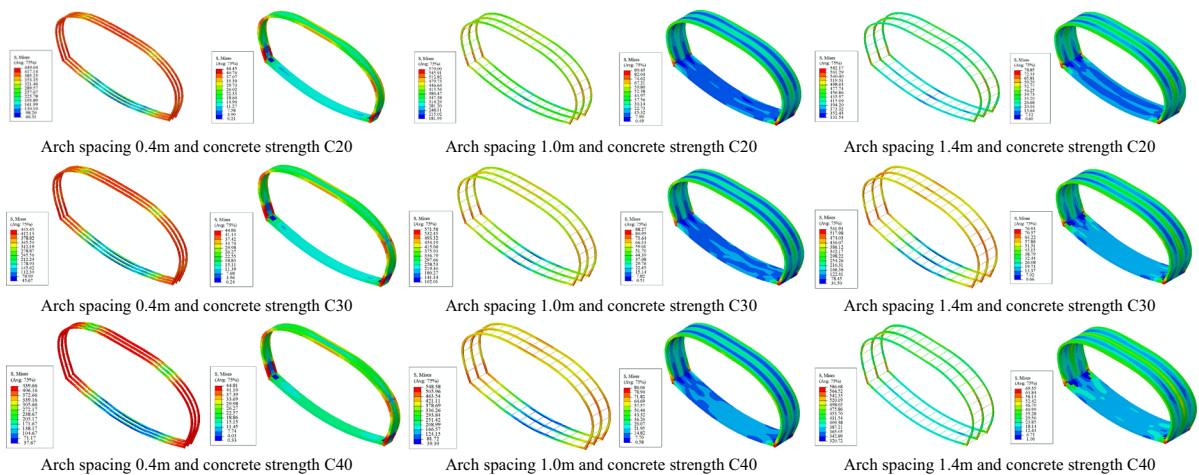


**Fig. 7** Axial force sharing ratio of initial supporting members

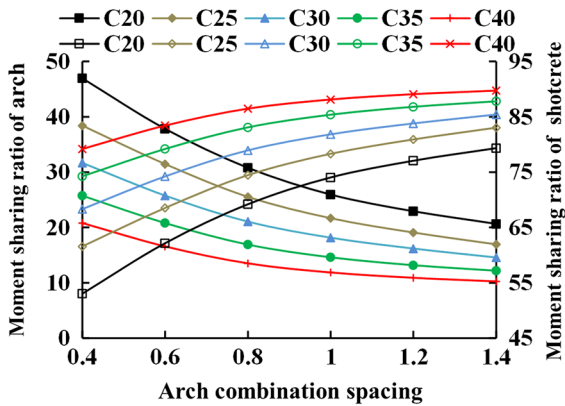
the strength of the concrete shotcrete. When the arch spacing is 0.4 m, the maximum difference of axial force sharing ratio of concrete shotcrete arch with adjacent strengths of C20, C25, C30, C35 and C40 is 4.17%, 3.36%, 2.53% and 1.62% respectively, and 2.00%, 1.68%, 1.41% and 1.08% respectively when the combined spacing of arch is 1.4 m.

#### (2) Bending moment share ratio, It can be seen from Fig. 8.

- A. The moment sharing ratio of arch decreases nonlinearly with the change of composite spacing, and the difference decreases gradually with the increase of concrete shotcrete strength. The moment sharing ratios of C20 and C40 concrete sprayed arches are



**Fig. 6** Stress nephogram of initial support components



**Fig. 8** Moment distribution of initial support components

46.97% and 20.81% respectively when the longitudinal connection spacing is 0.4 m, and 20.66% and 10.26% respectively when the spacing is 1.4 m, and 26.31% and 10.55% respectively.

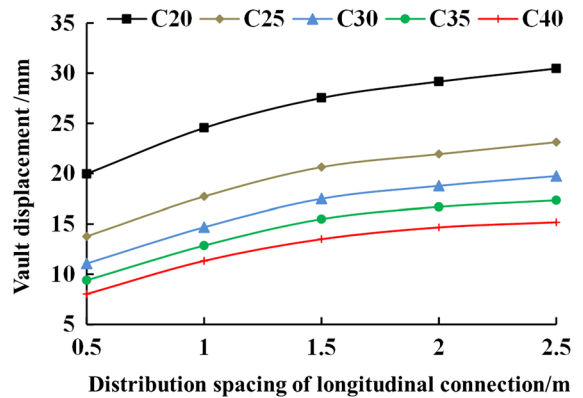
- B. With the increase of the strength of the concrete shotcrete, the difference of the moment sharing ratio of the arch is gradually reduced. When the combined spacing of arch is 0.4 m, the maximum difference of moment sharing ratio of concrete sprayed layer arch with adjacent strength of C20, C25, C30, C35 and C40 is 8.55%, 6.73%, 5.94% and 4.94% respectively; when the combined spacing of arch is 1.4 m, the maximum difference is 3.70%, 2.38%, 2.39% and 1.93% respectively.

### 3.3 The Coupling Bearing Effect of Concrete Shotcrete Strength and Longitudinal Connection Spacing

#### 3.3.1 Control Effect of Tunnel Deformation

As shown in Fig. 9,

- 1) With the increase of longitudinal connection spacing, the vault settlement difference decreases gradually under different concrete shotcrete strength, indicating that the skeleton effect of arch composite structure on concrete shotcrete decreases, and the control effect of initial support on tunnel deformation becomes worse and worse.



**Fig. 9** Effect of coupled bearing of concrete shotcrete strength and longitudinal connection spacing on tunnel deformation control

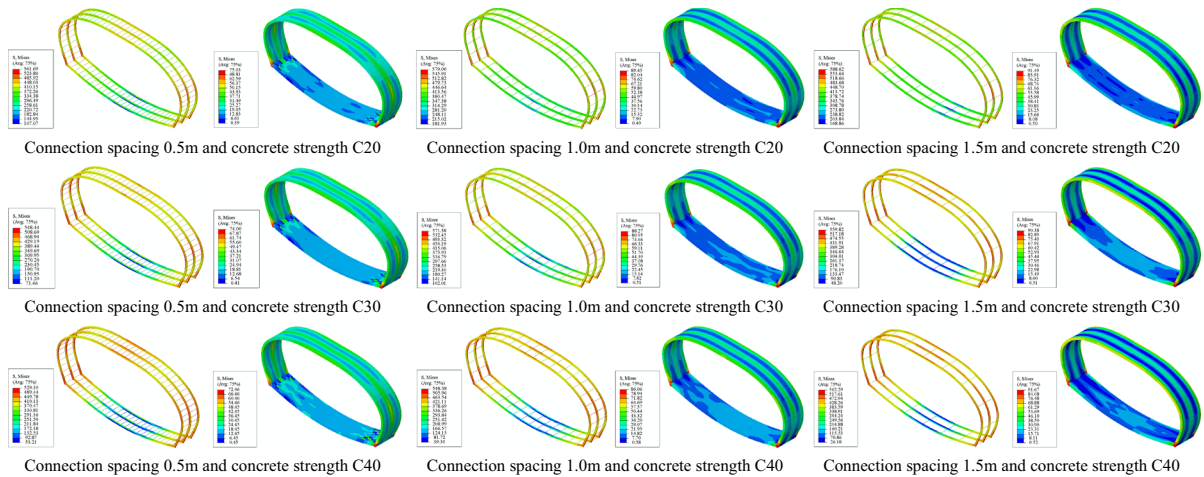
- 2) With the increase of concrete shotcrete strength, the vault settlement difference under different arch spacing conditions decreases gradually, which indicates that the load sharing effect of concrete shotcrete is getting smaller and smaller, and its effect on tunnel deformation control is getting smaller and smaller.

#### 3.3.2 Stress Distribution Law of Initial Supporting Members Under Coupling Effect

As shown in Fig. 10,

- (1) The strength of concrete shotcrete has an effect on the stress distribution of arch, the stress distribution of arch is uneven, and the stress concentration is obvious. With the increase of concrete shotcrete strength, the stress difference in the section of the stress concentration zone of arch increases, the diffusion of stress concentration zone of arch crown is not obvious, only appears in the outer flange, the stress concentration zone of arch waist and arch foot is gradually expanded, and the maximum stress in the stress concentration zone decreases slightly with the increase of concrete shotcrete strength. Under the influence of the skeleton effect of the arch, the high and low stress zones appear in the sprayed concrete layer, forming the “three high and two low” stress zones which are basically consistent with the geometric distribution of the arch in the initial support.





**Fig. 10** Nephogram of stress distribution of initial support components

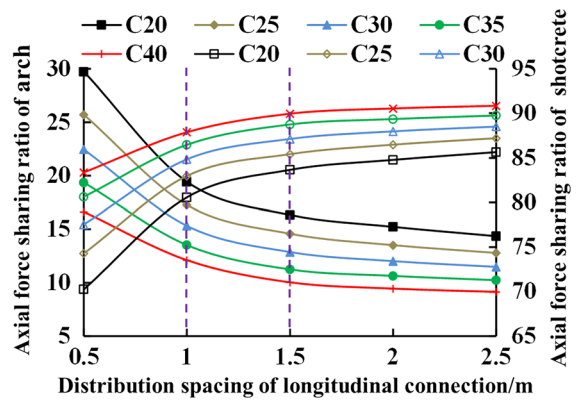
(2) With the increase of concrete strength, the stress distribution has little change, but the maximum value of stress decreases slightly. Compared with 0.5 m longitudinal joint spacing, the stress zoning is more obvious, and the low stress zone does not disappear at the arch shoulder. It shows that the longitudinal joint spacing has certain influence on the stress distribution of concrete shotcrete, and the distribution spacing of longitudinal joint is too small, so the whole skeleton of arch can be fully used to support and expand the stress of concrete shotcrete. Scope of influence.

### 3.3.3 Load Distribution Law of Initial Supporting Members Under Coupling Effect

According to the numerical test results, the ratio of axial force and bending moment between the shotcrete layer and the arch of the primary support member under the coupling action of the distribution spacing between the shotcrete layer and the longitudinal connection with different strength is drawn.

#### (1) Axial force sharing ratio

It can be seen from Fig. 11 that the difference of axial force sharing ratio of arch decreases gradually with the increase of concrete shotcrete strength under the condition of the same longitudinal connection spacing. When the combined spacing of arch is 0.5 m, the maximum difference of axial force sharing ratio of

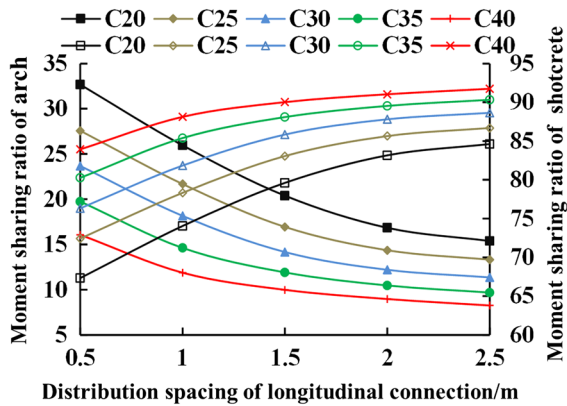


**Fig. 11** Axial force sharing ratio of initial support components

concrete sprayed layer arch with adjacent strength of C20, C25, C30, C35 and C40 is 4.03%, 3.25%, 3.08% and 2.74%, respectively; when the combined spacing of arch is 2.5 m, the values are 1.57%, 1.30%, 1.25% and 1.02% respectively.

(2) Bending moment share ratio, as shown in Fig. 12

A. The moment sharing ratio of arch decreases with the increase of longitudinal joint spacing, and the non-linearity of curve increases with the decrease of concrete shotcrete strength. The moment sharing ratios of C20 and C40 concrete sprayed arches are 32.68% and 16.07% respectively when the longitudinal connection spacing is



**Fig. 12** Bending moment sharing ratio of initial support members

0.5 m, and 15.38% and 8.25% respectively when the spacing is 2.5 m, which decrease 17.30% and 7.82% respectively.

- B. The difference of moment sharing ratio of arch decreases with the increase of concrete shotcrete strength under the condition of the same longitudinal joint spacing. When the combined spacing of arch is 0.5 m, the maximum difference of moment sharing ratio of concrete sprayed layer arch with adjacent strength of C20, C25, C30, C35 and C40 is 5.10%, 3.90%, 3.94% and 3.67% respectively; when the combined spacing of arch is 2.5 m, the maximum difference is 2.07%, 1.95%, 1.68% and 1.43% respectively.

## 4 Conclusions

- (1) The vault settlement decreases with the increase of the strength of the concrete shotcrete. When the strength of concrete shotcrete is C20, the vault settlement is close to the specified value of tunnel construction code. Taking the economic factors and intensity utilization ratio into account, C25 and C30 should be adopted for concrete shotcrete strength.
- (2) When the arch spacing exceeds 1.2 m, the difference of arch-top settlement is too large; when the spacing of longitudinal connection exceeds 1.5 m, the skeleton effect of arch

combination structure on concrete shotcrete decreases, and its effect on tunnel deformation control becomes smaller and smaller, and the effect of initial support on tunnel deformation is smaller and smaller. Control effect is getting worse and worse.

- (3) The concrete shotcrete takes on more axial forces, and the arch bears more bending moments. When the arch spacing is 0.4–0.8 m, the axial force sharing ratio of arch is 37.70–46.97%, which is too large; the bending moment sharing ratio of concrete shotcrete is 79.19–86.48%, which is too large. When the longitudinal connection spacing is 0.5–1.5 m, the axial force sharing ratio of the arch is 16.35–29.74%, and the concrete moment sharing ratio is 67.32–79.61%.
- (4) In order to give full play to the initial supporting capacity characteristics and control the tunnel deformation, it is suggested that the arch spacing and longitudinal connection should be 0.8–1.2 m and 0.5–1.5 m respectively under the condition of four-grade surrounding rock.

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