The Analysis of Elastic-Plastic Deformation Under Axial Tensile Force for Reinforcement Grout Sleeve

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Abstract. The grouted sleeve connector is the main type of tension node between precast concrete member and cast-in-place joint. This paper is focused on the stress-strain relation of different parts of the grouted sleeve connector to predict the axial force of the joint. According to grouted sleeve connector samples, the relationship of stress-strain for grouting material is a key point to predict the connection strength when an axial tension is applied. The connector is mainly composed of reinforced bar, grout material and metal sleeve. If taking this three parts into account, the stress-strain relation of grouting material will be able to deduced and so does the connection strength.

Keywords: Precast Concrete Members, Grouted Sleeve connector, Ultimate Bearing Capacity

1 Introduction

There are mainly three types of joint connection for reinforced bar: the grouted sleeve connection, steel sleeve joint and lapped joint of steel bar[1]. The lapped joints of steel bar cannot supply enough axial forces and it has been proved by experimental samples. As for steel sleeve joints, it cannot be applied because of the critical geometric position requirements[2-3]. Therefore the grouted sleeve connection turns to the only way to meet both the force and geometric position requirements. Grouted sleeve joints connect reinforced bars effectually and they can also deduce the welding time. If operated as required, the joint strength can fully meet the require- ments[4-5].

The axial strength of grouted sleeve joint is depends on the material strength of metal sleeve, the roughness of sleeve surface, the final setting strength of mortar, the anchorage length and etc[6]. Einea, Alias, Ling etc have taken the internal roughness of sleeve, mortar strength and the geometric dimension of reinforced bars into account[7-9]. But they have ignored the volume expansion caused by the failure surface between ribbed bars and mortar. Tao Wu[10-11], etc have derived the critical anchorage force, though the analysis of elastic deformation caused by the failure surface

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between ribbed bars and mortar. The shortage is the critical stress of failure stage has not derived.

Shilong Ju, Jianwei Chen[12], etc have quantified the relationship between axial force and different force model parameters thought calculation. And these parameters including the anchorage length of steel bar, longitudinal and transverse strain values and the failure surface between ribbed bars and mortar. Based on this, taking the anchorage length into account, Qiong Yv and Jingwen Wei[13] have computed the stress-strain relationship of anchorage strength under elastic and elastic-plastic condition. But the axial force of further failure tendency it still to be not reached in elastic-plastic condition.

In grouted sleeve joints, the adhesive force on the surface between ribbed bars and mortar depends on the final setting strength of mortar, the geometric dimension of medal sleeve and the related mechanical properties of materials[14]. Based on the final setting strength of mortar, this paper take metal sleeve's geometric parameters, mechanical property, lateral restraint condition into account, has derived the axial force in elastic and elastic-plastic condition. Compared with experimental results, the critical axial force has taken discrete particle characteristics of mortar"s failure state into account and calculated the ultimate holding force of steel bars when sand volume expansion model occurred.

2 The Relationship Between Final Setting Strength of Mortar and Axial Force of Reinforced Bar under Elastic Condition

The reinforced bars of concrete cast-in-place parts should be insert into the metal sleeve of precast concrete member for a certain length. Mortar should be injected into the sleeve solidly after reinforced bars are imposition. When the mortar's strength builds up, all parts of the grouted sleeve are formed into a whole system. As Fig 1 shows.

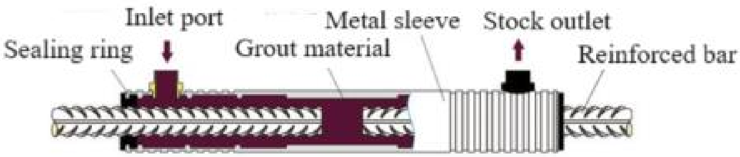

Fig. 1. the Components of Large Diameter Anchor

According to Fig. 1, the interior space between metal sleeve and reinforced bar should be filled with grout material which is often used of mortar. During the process of axial force is applied, the reinforced bar and mortar rub against each other and it caused Volume expansion. This circumferential expansion is restrained by both metal grouted sleeve and precast concrete.

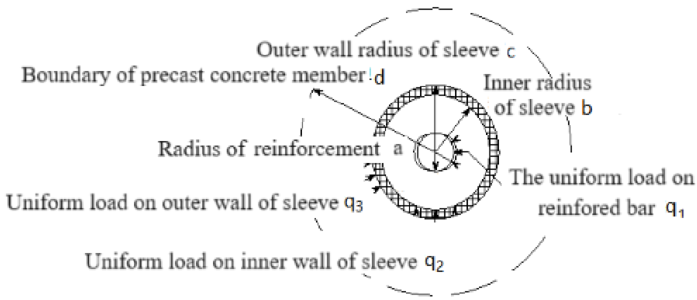

Fig. 2. The Cross Section of Grouted Sleeve Connection

According to the elastic thick-walled cylinder model of Fig. 2, precast concrete member is the outermost cylinder layer, metal sleeve is the middle layer and the grout material is the inner layer. The radial and circumferential stresses can be calculated as follow.

$$\begin{cases} \sigma_\rho = \dfrac{c^2 q_3}{d^2 - c^2}\left(1 - \dfrac{d^2}{\rho^2}\right) \\ \sigma_\phi = \dfrac{c^2 q_3}{d^2 - c^2}\left(1 + \dfrac{d^2}{\rho^2}\right) \end{cases} \tag{1}$$

In equation 1, ρ is the radial distance between the rein- forced bar canter and calculating point, ϕ is circumferential distance between the two points. The radial stress σ_ρ is a key parameter to deduce the maximum axial force and it can be derived though equation 1. The common size of grouted sleeves is $d = 3c$ represented in figure 1.

$$\sigma_\rho \Big|_{\rho=c} = \frac{d^2 q_3}{d^2 - c^2}\left(1 - \frac{d^2}{\rho^2}\right) = -q_3 \tag{2}$$

As for metal sleeve, the uniform load on the outer wall sleeve is q_3, the uniform load on the inter wall sleeve is q_2.The circumferential tensile stress is computed in figure 1.

$$\begin{cases} \sigma_\rho = \dfrac{b^2 c^2}{c^2 - b^2}\dfrac{q_3 - q_2}{\rho^2} + \dfrac{b^2 q_2 - c^2 q_3}{c^2 - b^2} \\ \sigma_\phi = \dfrac{b^2 c^2}{c^2 - b^2}\dfrac{q_3 - q_2}{\rho^2} + \dfrac{b^2 q_2 - c^2 q_3}{c^2 - b^2} \end{cases}$$

Based on the mechanical model of a thick-walled cylinder, the relationship between q_3 and q_2 is as follows.

$$\int_{-\pi/2}^{\pi/2} -q_3 \cos\phi c d\phi + 2\int_b^c \frac{b^2c^2}{c^2-b^2}\frac{q_3-q_2}{\rho^2} + \frac{b^2q_2-c^2q_3}{c^2-b^2} d\rho = \int_{-\pi/2}^{\pi/2} -q_2 \cos\phi b d\phi$$

$$= \int_{-\pi/2}^{\pi/2} -q_2 \cos\phi b d\phi$$

The equation can be simplified as:

$$q_3 = \frac{b}{c} q_2 \tag{3}$$

The relationship between q_2 and q_1 can be deduced in the same way.

$$q_2 = \frac{a}{b} q_1 \tag{4}$$

The radial displacement on the surface between mortar and reinforced bar can be computed as follows.

$$u_\rho = \frac{1-\upsilon^2}{E}\left[-\left(1+\frac{\upsilon}{1-\upsilon}\right)\frac{A_G}{\rho} + 2\left(1-\frac{\upsilon}{1-\upsilon}\right)C_G\rho\right]$$

$$A_G = \frac{a^2b^2(q_2-q_1)}{b^2-a^2}, C_G = \frac{q_1a^2-q_2b^2}{2(b^2-a^2)}$$

According to the relationship shown in equation 4, the relationship between radial deformation u_ρ and q_1 can be shown in equation 5.

$$u_p = \frac{1+\upsilon^2}{E}\left[-\left(1+\frac{\upsilon}{1-\upsilon}\right)\frac{a^2b^2(q_2-q_1)}{\rho(b^2-a^2)} + \right.$$

$$\left. 2\left(1-\frac{\upsilon}{1-\upsilon}\right)\frac{q_1a^2-q_2b^2}{2(b^2-a^2)}\rho\right] \tag{5}$$

The above equation can be simplified as:

$$\begin{cases} u_\rho = q_1\dfrac{1-\upsilon^2}{E}\left[\dfrac{1}{1-\upsilon}\dfrac{a^2b}{\rho(b+a)} - \dfrac{1-2\upsilon}{1-\upsilon}\dfrac{a}{b-a}\rho\right] \\ u_\phi = 0 \end{cases} \tag{6}$$

According to the relationship between radial deformation u_ρ and q_1, the radial pressure σ_ρ is deduced when the grout is in a critical cracking state.

3 Ultimate tensile force and yield criterion of sleeve grouting connection under elastoplastic condition

When the steel bar is strained, the holding force of the grout material on the steel bar mainly includes the following two aspects：1) the adhesion on the surface of grout material and steel bar; 2) under the axial tense, the increasing of adhesion force caused by the section of grout expands.

The surface's relative slip between steel bar and grout material occurs under elastoplastic condition, and it reduces the adhesion force obviously. A loose, discrete slip area occurs on the surface and the area causes volume expansion which follows the yield model of sand dilatancy.

3.1 The ultimate tensile force of the sleeve grouting connection at the initial elastoplastic stage

The axial force of steel bar causes circumferential strain of grout material because of cracking, especially in the initial yield state.

$$\varepsilon_\phi = \frac{1}{\rho}\frac{\partial u_\phi}{\partial \phi} + \frac{u_\rho}{\rho} \tag{7}$$

As the code for design of concrete structures required, once the strain of grout material rise up to the cracking control point ε_0, the corresponding radial uniform q_1 should be as follows.

$$\varepsilon_0 = q_1 \frac{1-\upsilon^2}{E}\left[\frac{1}{1-\upsilon}\frac{a^2 b}{\rho^2 (b+a)} - \frac{1-2\upsilon}{1-\upsilon}\frac{a}{b-a}\right] \tag{8}$$

With equation 8, the stress-strain relation between q_1 and ε_0 is expressed though an analytical solution for the grout sleeve system at elastoplastic state.

3.2 The ultimate tensile force of sleeve grouting connection in elastoplastic development stage

When the axial tension increases, the adhesive force between the grout material and the steel bar surface gradually decreases and disappears. At the same time, a loose, discrete slip area occurs between the steel bar and grout material, which causes volume expansion show in figure 3.

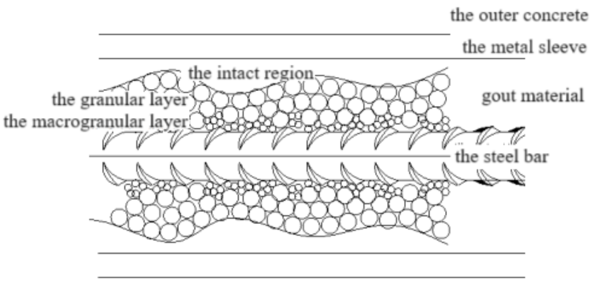

Fig. 3. The elastic-plastic Deformation of Grouted Sleeve Connection

When the stress-strain relation develops, the adhesive force c between gout material and steel bar disappears gradually, and a loose, discrete slip area increases with its volume expends. The granular and micro-granular layer are similar to the failure mode of sand dilatancy as shown in figure 3 and equation 9.

$$\tau_1 = c + \sigma_\rho \tan\varphi \tag{9}$$

In the advanced state of elastoplastic deformation, the critical strength is as follows in equation 10 with the failure mode of sand dilatancy.

$$\tau_2 = \sigma \tan\varphi \tag{10}$$

During the whole process of stress-strain relation develops, the adhesive force c disappears gradually, and the dilatancy force $\sigma\tan\varphi$ caused by volume expends because of the grouted material cracking.

$$\tau = c(\varepsilon) + \sigma\tan\varphi \tag{11}$$

In equation 11, $c(\varepsilon)$ is the adhesive force c between grout material and steel bar taking circumferential strain ε into account. At the beginning of elastoplastic deformation, the adhesive force c is the largest and the circumferential strain ε equals to 0. That is $c(\varepsilon) = b - a\varepsilon$, $\varepsilon \in (\varepsilon_0, b/a)$.

4 Example analysis

The rebar - sleeve connection system is mainly be composed of the grouted material and reinforce bar. The axial tension is mainly provided by the adhesive force and dilatancy force together. The former exists in elastic state and the beginning of elasto-plastic stage and the later is made full use of at the advance elastoplastic state.

4.1 Streets-strain relation analysis of sleeve-external concrete in elastic state

The uniform q_1 applied on steel bar is related to the circumferential displacement u_φ and radical displacement u_ρ under elastic state. According to figure 2 and equation 8, the critical strain of grouted material is ε_0. And the stress-strain relation between q_1 and ε_0 is able to deduce though parameter u_ρ.

$$q_1 = \varepsilon_0 \bigg/ \left[\frac{1-\upsilon^2}{E} \left(\frac{1}{1-\upsilon} \frac{a^2 b}{\rho^2 (b+a)} - \frac{1-2\upsilon}{1-\upsilon} \frac{a}{b-a} \right) \right]$$
$$= 0.002 \bigg/ \left[\frac{1-0.3^2}{3\times 10^4} \left(\frac{1}{1-0.3} \cdot \frac{3.9}{4.9} - \frac{1-2\times 0.3}{1-0.3} \cdot \frac{1}{2.9} \right) \right]$$
$$= 26.85\text{MPa}$$

On the contact surface of grouted material and steel bar, the uniform load on steel bar q_1 is able to compute by equation 8, as if ε_0 is confirmed. According to the experiment, the diameter of steel bar is 18mm, the inter radius of sleeve is 70mm, the thickness of sleeve wall is 3mm.

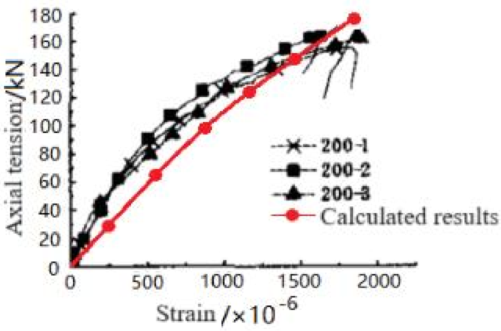

Fig. 4. The Relationship between Stress-strain of Grouted Sleeve Connection

The calculated result is shown in figure 4, taking the adhesive force of steel bar and grout and the dilatancy force caused by volume expansion into account. The grouted sleeve connection is composed of steel bar with 18 mm diameter and 200mm insertion depth. The results are the relation between the axial load and corresponding circumferential strain. According to the results, calculated data are more like a straight line of linear elasticity, which is basically consistent with the experimental test results.

4.2 Simulation of elastoplastic force of experimental rebar - sleeve model

Once the the failure form is the relative sliding of steel bar and grout material, the relation of ε_0 and u_ρ can be computed with equation 8, according to the experiment.

$$u_\rho = q_1 \frac{1-\upsilon^2}{E}\left[\frac{1}{1-\upsilon}\frac{a^2 b}{\rho(b+a)} - \frac{1-2\upsilon}{1-\upsilon}\frac{a}{b-a}\rho\right]$$

$$= 26.85 \cdot \frac{1-0.3^2}{3\times10^4}\cdot\left[\frac{1}{1-0.3}\cdot\frac{3.9}{4.9}\cdot 9 - \frac{1-2\times0.3}{1-0.3}\cdot\frac{1}{2.9}\cdot 9\right]$$

$$= 0.018mm$$

If the failure form is the relative sliding of steel bar and grout material, figure 5 shows the load-deformation relation.

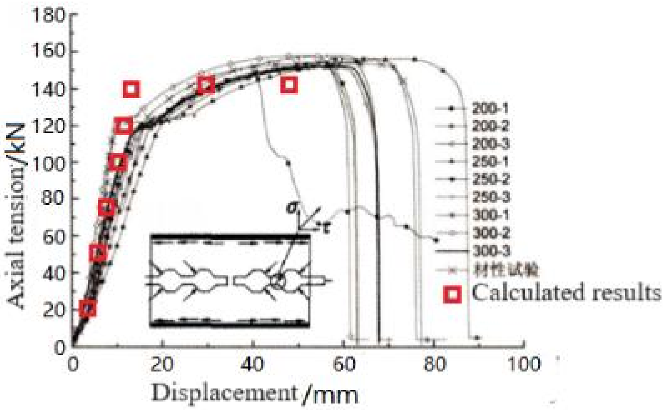

Fig. 5. The the Elastic-plastic Deformation between Steel and Grout Material

In the state of elastoplastic deformation, cracking strain of grouted material ε_0 is defined as the starting point of plasticity development of rebar - grout system. Taking equation $\tau_1 = c + \sigma \tan\varphi$ as the basic yield criterion, when the stress-strain relation develops, the adhesive force between gout material and steel bar disappears gradually, and a loose, discrete slip area increases with its volume expends. According to figure 5, the elastic stress-deformation trend of reinforced grout system can be simulated by using elastic thick-walled cylinder model. In the elastoplastic state, it is available to apply stress-strain relation of soil, from clay to sand dilatancy model, to simulate grouted sleeve connection's deformation under axial tension.

5 Conclusion

The stress-strain relation of grouted sleeve connection can be simulated though stress-strain models of soil and the elastic thick-walled cylinder:

1) The deformation for interactive system of sleeve -grouted material- rebar under critical axial tension is derived though the elastic thick-walled cylinder model and the failure mode of sand dilatancy.

2) With the parameters of C and φ in Mohr- Coulomb yield criterion in soil mechanics, the grouted material's stress-strain relation is effectively predicted though the process of hardened grout from cracking to granular collapse.

According to the experiment results, the deformation and stress of grouted sleeve connections can be well fitted under elastic and elastic-plastic forces.

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