

## Research Article

### Analysis of Cracking Mode of Anchor Structure of Underground Engineering Induced by Reinforcement Corrosion

<sup>1</sup>Wantao Ding and <sup>2</sup>Jinhui Liu

<sup>1</sup>Geotechnical and Structural Engineering Research Center, Shandong University, Jinan 250061, China

<sup>2</sup>Department of Civil Engineering, Shandong Jiaotong University, Jinan 250023, China

**Abstract:** Based on elastic theory and assumption of maximum tensile-stress failure criterion, together with construction process of anchor structure and rust expansion critical process, this study proposed a simplified reinforcement rust expansion mechanical model of anchor structure system. Elastic criterion of different initial cracking mode was rewarded under different stress ratios. According to analysis of critical cracking mode of different medium, cracking order of mortar and surrounding rock depended on their material parameters, in-situ stress and thickness of mortar cover. Critical cracking conditions of different medium without effect of in-situ stress was the same as that of considering in-situ stress while  $k$  is equal to 3 or 1/3. And engineering example shows that three different cracking modes exist under different stress ratios. The result provides a useful reference for analysis of mechanical deterioration mechanism of anchor structure and design of support structure of underground engineering.

**Keywords:** Anchor structure system, critical cracking mode, elastic theory, maximum tensile-stress failure criterion, reinforcement corrosion

## INTRODUCTION

Reinforcement corrosion is one of important factors to cause degradation of RC structure. The corrosion products normally occupy a much larger volume than the steel removed due to reinforcement corrosion, when exposed to complex erodibility environment. Corrosion products then accumulate in the concrete-steel Interface Transition Zone (ITZ), generate expansive pressure on the surrounding concrete and cause these cracks to propagate, spalling or delamination of the concrete. And, finally, the expansive pressure result in bearing capacity reducing and durability deterioration of RC structure. Reinforcement corrosion is extremely popular in bridge decks, coastal structures *et al.* And it is easy to be found. Domestic and foreign scholars study widely the effect of reinforcement corrosion for RC structure and a series of research results were rewarded (Basheer *et al.*, 1996; Almusallam *et al.*, 1996; Jin *et al.*, 2001; Zhao and Jin, 2002; Fang *et al.*, 2004; Xia and Ren, 2006; Dong and Mahadevan, 2008; Wang and Zheng, 2009; Shi and Sun, 2010; Chen *et al.*, 2010). Due to wicked underground corrosion environment, serious reinforced corrosion also existed in anchor structure of underground engineering. It can result in crack in the anchorage body or surrounding rock mass, so anchor mechanical performance was deteriorated and

durability of anchor structure was degraded. However, because of its concealment, the study on bolts rust expansion in anchor structure of underground engineering was less (Zeng *et al.*, 2004; Zhao *et al.*, 2007; He and Lei, 2007; Xu *et al.*, 1990).

Analyzing synthetically current research, it is different for boundary condition of corrosion cracking model, stress state and research object between anchorage system of underground engineering and RC structure. There are only two different materials (steel and concrete) in RC structure. With the increase of reinforcement corrosion, expansive pressure on surrounding concrete will cause crack initiation and propagation and, finally penetrating crack of concrete will follow. But there are three different materials (steel, mortar and surrounding rock) in anchor structure. Hence, during the process of bolts rust expansion, expansive pressure can not only cause cracking in mortar layer, but also in surrounding rock, especially for the surrounding rock mass with micro cracks. According to research results of RC structure, current study on bolts rust expansion of underground engineering only considers cracking of mortar layer to deteriorate the mechanical performance of anchor system. However, stress state of anchor structure is more complex than that of RC structure and surrounding constraint medium is different between anchor structure and RC structure, the cracking in rock

**Corresponding Author:** Wantao Ding, Geotechnical and Structural Engineering Research Center, Shandong University, Jinan 250061, China, Tel.: 13698610960

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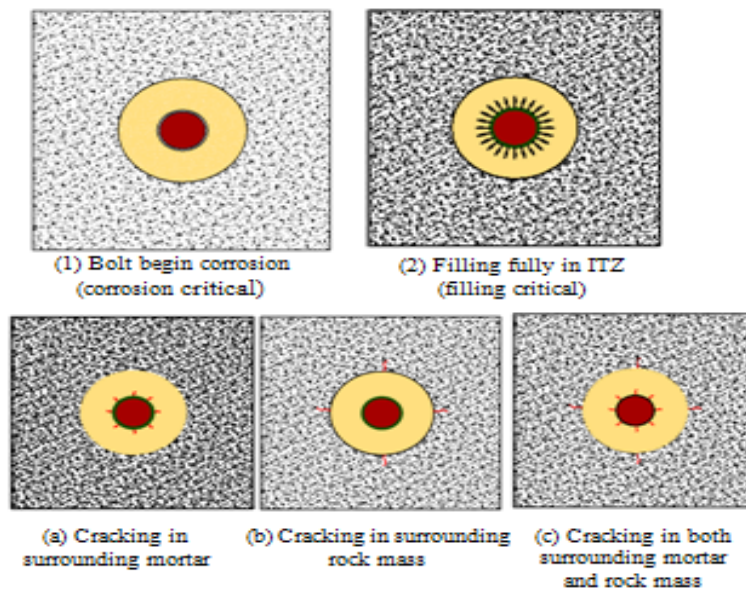


Fig. 1: Cracking process of anchor rust expansion

mass surrounding mortar layer and cracking order between mortar layer and surrounding rock mass will result in different deterioration effect for mechanical performance of anchor structure in underground engineering during the progress of rust expansion. Hence, based on elastic theory, the purposes is to study cracking model of anchor system in underground engineering under different combined stress. It can provide theoretical basis to analyze the deterioration mechanism of mechanical performance of anchor system and design supporting structure of underground engineering.

### MATERIALS EXPANSION PROCESS

There are three kinds of main factors to result in reinforcement corrosion. They are: carbonization of the concrete cover, chloride penetration and induction of stray current. For bolts in anchor structures of underground engineering, the damage caused by chloride penetration is the most serious. The entire chloride-induced reinforcement corrosion process of reinforced concrete structures or anchor structures of underground engineering can be divided roughly into three phases as shown in Fig. 1. The three phases are corresponding to three critical points. The first phase is characterized by the chloride penetration, during which the chloride diffuses gradually from the concrete or rock surface through the concrete or mortar cover toward the reinforcement. When the chloride content at reinforcement reaches a threshold value to initiate the corrosion process, its critical point is corrosion critical. The second phase is dominated by the reinforcement rust expansion, during which the rust (i.e., the corrosion products) accumulates in the concrete-steel ITZ. When

voids in ITZ are occupied completely with the rust, its critical point is filling critical. The further rust accumulation will trigger expansive stress and then cracking in the surrounding concrete, mortar or rock mass, which indicates the start of the third phase. During the third phase, the rust expansion-induced cracks propagate in concrete or mortar surrounding the reinforcing steels until some critical failure mode, even cracks propagate can appear in surrounding rock mass. The occurrence mechanism in three phases is the same. The different appears in the third phase. Its critical cracking model is different between RC structures and anchor structures of underground engineering. Only cracking model in the surrounding concrete appears in RC structures, but there can be three critical cracking models in anchor structures of underground engineering. They are: initial cracking appearing firstly in surrounding mortar layer, initial cracking appearing firstly in surrounding rock mass or cracking appearing synchronously in both surrounding mortar layer and rock mass.

### ANALYSIS METHODS

Based on elastic theory and the following hypotheses, cracking model of anchor structures of underground engineering at critical time of bolts rust expansion is analyzed (Fig. 2). According to the installation procedures and rust expansion process of rock bolts, mechanical model of bolts rust expansion is simplified (Xu, 1990).

**Assumption 1:** The different medium surrounding the reinforcing anchor is in elastic state when critical cracking appearing.

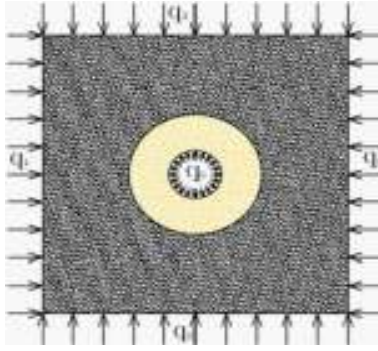


Fig. 2: Simplified mechanical model of anchor rust expansion

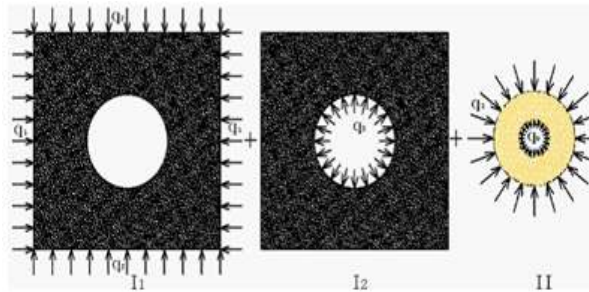


Fig. 3: Equivalent mechanical model

$q_0$ : Critical rust expansive stress;  $q_1$  and  $q_2$ : Pressure of surrounding rock mass related to in-situ stress;  $q_3$ : Stress of interface between mortar layer and surrounding rock mass caused by  $q_0$

**Assumption 2:** The thickness of anchor corrosion layer and ITZ are neglected.

**Assumption 3:** The rust expansive stress is uniform along the full anchor.

Figure 2 can be equivalent to Fig. 3 at the basis of elastic accumulative theory.

### ANALYSIS RESULTS

**Hoop stress in surrounding rock mass:** The forced model of surrounding rock mass can be equivalent to two mechanical models (I1 and I2) as shown in Fig. 3. Based on elastic accumulative theory, the hoop stress  $\sigma_{\theta 1}$  in any points of surrounding rock mass can be expressed as:

$$\sigma_{\theta 1} = \frac{q_1 + q_2}{2} \left(1 + \frac{b^2}{r^2}\right) - \frac{q_1 - q_2}{2} \left(1 + 3\frac{b^4}{r^4}\right) \cos 2\theta - \frac{b^2}{r^2} q_3 \quad (1)$$

**Hoop stress in surrounding mortar layer:** The forced model of surrounding mortar layer can be equivalent to model II as shown in Fig. 3. So the hoop stress  $\sigma_{\theta 2}$  in any points of surrounding mortar layer can be expressed as:

$$\sigma_{\theta 2} = -\frac{a^2(b^2 + r^2)}{r^2(b^2 - a^2)} q_0 + \frac{b^2(a^2 + r^2)}{r^2(b^2 - a^2)} q_3 \quad (2)$$

**Partition coefficient of internal pressure:** Partition coefficient of internal pressure  $\lambda$  is defined as the ratio of  $q_3$  to  $q_1$  and  $\lambda$  also takes the form (Xu, 1993):

$$\frac{1}{\lambda} = 1 + \alpha(t - 1) \quad (3)$$

where  $\alpha$  is equal to:

$$\frac{E_1(\mu_2 + 1) + E_2(\mu_1 + 1)(1 - 2\mu_1)}{2(1 - \mu_1^2)E_2}$$

where,

$t$  : The ratio of  $b^2$  to  $a^2$

$\mu_1$  &  $E_1$  : Poisson ratio and elastic modulus of mortar

$\mu_2$  &  $E_2$  : Poisson ratio and elastic modulus of rock mass

It can be observed in Eq. (3) that are as follows:

- $\lambda$  is equal to  $a^2/b^2$  when two contacting materials are the same.
- There is a linear relationship between  $1/\lambda$  and  $b^2/a^2$ ,  $\lambda$  related to the thickness of mortar layer, Poisson ratio and elastic modulus of different material. And it decreases with increasing the thickness of mortar layer.

Employing  $q_3 = \lambda q_0$  and using Eq. (1) and (2), leads to:

$$\sigma_{\theta 1} = \frac{q_1 + q_2}{2} \left(1 + \frac{b^2}{r^2}\right) - \frac{q_1 - q_2}{2} \left(1 + 3\frac{b^4}{r^4}\right) \cos 2\theta - \frac{b^2}{r^2} \lambda q_0 \quad (4)$$

$$\sigma_{\theta 2} = \frac{a^2 b^2 (\lambda - 1) + r^2 (\lambda b^2 - a^2)}{r^2 (b^2 - a^2)} q_0 \quad (5)$$

**Hoop stress at cracking planes of surrounding rock mass:** Equation (4) shows that the maximum hoop tensile-stress in surrounding rock mass should appear at the hoop plane which its radius  $r$  is equal to parameter  $b$  and the hoop stress at cracking face can be expressed as:

$$\sigma_{\theta 1} = q_1 + q_2 - 2(q_1 - q_2) \cos 2\theta - \lambda q_0 \quad (6)$$

Employing  $q_2 = Kq_1$  and using Eq. (6), leads to:

$$\sigma_{\theta 1} = [(1 - 2 \cos 2\theta) + (1 + 2 \cos 2\theta)K] q_1 - \lambda q_0 \quad (7)$$

Without considering the effect of in-situ stress, that is  $q_1 = q_2 = 0$ , then:

$$\sigma_{\theta 1} = -\lambda q_0 \quad (8)$$

It should be noted that tensile-stress of points at the cracking plane related to the angel from Eq. (7). And derivation calculus to Eq. (7) that shows:

$$\partial \sigma_{\theta 1} / \partial \theta = 4 \sin 2\theta (1 - K) q_1 \quad (9)$$

Applying  $\partial \sigma_{\theta 1} / \partial \theta = 0$  gives:

$$K = 1 \text{ or } \sin 2\theta = 0$$

$$1) K = 1, \sigma_{\theta 1} = 2q_1 - \lambda q_0 \quad (10)$$

2)  $\sin 2\theta = 0$ , that is  $\cos 2\theta = \pm 1$ :

- $\cos 2\theta = 1, \theta = n\pi$  ( $n = 0, 1, 2, \dots$ ):

$$\sigma_{\theta 1} = (3K - 1)q_1 - \lambda q_0 \quad (11)$$

- $\cos 2\theta = -1, \theta = (2n + 1)\pi/2$  ( $n = 0, 1, 2, \dots$ ):

$$\sigma_{\theta 1} = (3 - K)q_1 - \lambda q_0 \quad (12)$$

**Hoop stress at cracking planes of surrounding mortar:** Equation (5) shows that the maximum hoop tensile-stress in surrounding mortar should appear at the hoop plane which its radius  $r$  is equal to parameter  $a$  and the hoop stress at cracking face can be expressed as:

$$\sigma_{\theta 2} = -\frac{a^2 - (2\lambda - 1)b^2}{b^2 - a^2} q_0 \quad (13)$$

**Critical cracking model analysis of different medium under bolts rust expansion:** Assumption that ultimate tensile strength of mortar is  $f_m$  and that of rock mass is  $f_r$  and defined as  $f_m/f_r = \Psi$ . The hoop tensile-stress in medium surrounding anchor increased gradually with increase of rust expansion stress during the process of bolts rust expansion. When the maximum hoop tensile-stress at a certain point of medium reaches the ultimate tensile strength, the cracks will appears in medium. The compressive stress is defined as positive and tensile stress is defined as negative under the analysis process of cracking model. So the hoop tensile-stress and ultimate tensile strength ( $\sigma_{\theta 1}, \sigma_{\theta 2}, f_r$  and  $f_m$ ) are negative value. The in-site stress and critical rust expansion stress ( $q_1, q_0$ ) are positive value.

**Un-considering *in-situ* stress:**

- **Cracking condition analysis of mortar:** While mortar cracking, conditions need to be satisfied as:

$$\sigma_{\theta 2} = f_m \text{ and } \sigma_{\theta 1} > f_r$$

thus,

$$\alpha t^2 - (1 + \psi)t + (\psi + 1 - \alpha) > 0 \quad (14)$$

- **Crack condition analysis of both mortar and rock mass:** While both mortar and rock mass cracking at the same time, conditions need to be satisfied as:

$$\sigma_{\theta 2} = f_m \text{ and } \sigma_{\theta 1} = f_r$$

thus,

$$\alpha t^2 - (1 + \psi)t + (\psi + 1 - \alpha) = 0 \quad (15)$$

- **Cracking condition analysis of rock mass:** While rock mass cracking, conditions need to be satisfied as:

$$\sigma_{\theta 1} = f_r \text{ and } \sigma_{\theta 2} > f_m$$

thus,

$$\alpha t^2 - (1 + \psi)t + (\psi + 1 - \alpha) < 0 \quad (16)$$

**Considering *in-situ* stress:**

- **Cracking condition analysis of mortar:** While mortar cracking, conditions need to be satisfied as:

$$\sigma_{\theta 2} = f_m \text{ and } \sigma_{\theta 1} > f_r$$

therefore,

- $K = 1$ :

$$\frac{q_1}{q_0} > \frac{-\alpha t^2 + (1 + \psi)t - (\psi + 1 - \alpha)}{2\psi(t - 1)(\alpha t + 1 - \alpha)} \quad (17)$$

- $0 \leq K < 1/3$ :

$$\frac{q_1}{q_0} < \frac{-\alpha t^2 + (1 + \psi)t - (\psi + 1 - \alpha)}{(3K - 1)\psi(t - 1)(\alpha t + 1 - \alpha)} \quad (18)$$

- $1/3 < K < 1$ :

$$\frac{q_1}{q_0} > \frac{-\alpha t^2 + (1 + \psi)t - (1 + \psi - \alpha)}{(3K - 1)\psi(t - 1)(\alpha t + 1 - \alpha)} \quad (19)$$

Table 1: Material parameters of mortar and rock

| Material type | Density $\rho/\text{Kg/m}^3$ | Elastic modulus $E/\text{Gpa}$ | Possion ratio $\mu$ | Tensile strength $f_t/\text{Mpa}$ |
|---------------|------------------------------|--------------------------------|---------------------|-----------------------------------|
| Mortar        | 2400                         | 30                             | 0.20                | 3                                 |
| Rock          | 2650                         | 15                             | 0.25                | 2                                 |

- $1 < K < 3$ :

$$\frac{q_1}{q_0} > \frac{-\alpha t^2 + (1 + \psi)t - (1 + \psi - \alpha)}{(3 - K)\psi(t - 1)(\alpha t + 1 - \alpha)} \quad (20)$$

- $K > 3$ :

$$\frac{q_1}{q_0} < \frac{-\alpha t^2 + (1 + \psi)t - (1 + \psi - \alpha)}{(3 - K)\psi(t - 1)(\alpha t + 1 - \alpha)} \quad (21)$$

- $K = 3$  or  $K = 1/3$ :

$$\alpha t^2 - (1 + \psi)t + (1 + \psi - \alpha) > 0 \quad (22)$$

- **Cracking condition analysis of both mortar and rock mass:** While both mortar and rock mass cracking at the same time, conditions need to be satisfied as:

$$\sigma_{\theta 2} = f_m \text{ and } \sigma_{\theta 1} = f_r$$

therefore,

- $K = 1$ :

$$\frac{q_1}{q_0} = \frac{-\alpha t^2 + (1 + \psi)t - (1 + \psi - \alpha)}{2\psi(t - 1)(\alpha t + 1 - \alpha)} \quad (23)$$

- $0 \leq K < 1/3$  or  $1/3 < K < 1$ :

$$\frac{q_1}{q_0} = \frac{-\alpha t^2 + (1 + \psi)t - (1 + \psi - \alpha)}{(3K - 1)\psi(t - 1)(\alpha t + 1 - \alpha)} \quad (24)$$

- $1 < K < 3$  or  $K > 3$ :

$$\frac{q_1}{q_0} = \frac{-\alpha t^2 + (1 + \psi)t - (1 + \psi - \alpha)}{(3 - K)\psi(t - 1)(\alpha t + 1 - \alpha)} \quad (25)$$

- $K = 3$  or  $K = 1/3$ :

$$\alpha t^2 - (1 + \psi)t + (1 + \psi - \alpha) = 0 \quad (26)$$

- **Cracking condition analysis of rock mass:** While rock mass cracking, conditions need to be satisfied as:

$$\sigma_{\theta 1} = f_r \text{ and } \sigma_{\theta 2} > f_m$$

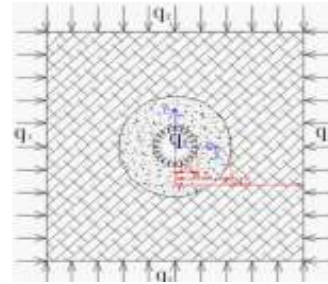


Fig. 4: Mechanical model of anchor rust expansion

Table 2: Coefficient relation to material and model

| $\alpha$ | t    | $\psi$ |
|----------|------|--------|
| 1.677    | 2.25 | 1.5    |

therefore,

- $K = 1$ :

$$\frac{q_1}{q_0} < \frac{-\alpha t^2 + (1 + \psi)t - (1 + \psi - \alpha)}{2\psi(t - 1)(\alpha t + 1 - \alpha)} \quad (27)$$

- $0 \leq K < 1/3$ :

$$\frac{q_1}{q_0} > \frac{-\alpha t^2 + (1 + \psi)t - (1 + \psi - \alpha)}{(3K - 1)\psi(t - 1)(\alpha t + 1 - \alpha)} \quad (28)$$

- $1/3 < K < 1$ :

$$\frac{q_1}{q_0} < \frac{-\alpha t^2 + (1 + \psi)t - (1 + \psi - \alpha)}{(3K - 1)\psi(t - 1)(\alpha t + 1 - \alpha)} \quad (29)$$

- $1 < K < 3$ :

$$\frac{q_1}{q_0} < \frac{-\alpha t^2 + (1 + \psi)t - (1 + \psi - \alpha)}{(3 - K)\psi(t - 1)(\alpha t + 1 - \alpha)} \quad (30)$$

- $K > 3$ :

$$\frac{q_1}{q_0} > \frac{-\alpha t^2 + (1 + \psi)t - (1 + \psi - \alpha)}{(3 - K)\psi(t - 1)(\alpha t + 1 - \alpha)} \quad (31)$$

- $K = 3$  or  $K = 1/3$ :

$$\alpha t^2 - (1 + \psi)t + (1 + \psi - \alpha) < 0 \quad (32)$$

where the parameters  $\alpha$  and  $\psi$  relate to mortar and rock mass, the parameter K relates to in-situ stress. They are obtained by test and experience  $t = b^2/a^2$ .

Table 3: Critical cracking conditions of different cracking mode

| Cracking model         | Cracking conditions                           |            |            |                               |                            |          |                        |                    |
|------------------------|---|------------|------------|-------------------------------|----------------------------|----------|------------------------|--------------------|
|                        | $\alpha^2 - (1 + \psi) + (1 + \psi - \alpha)$ |            |            | $q_1/q_0$                     |                            |          |                        |                    |
|                        | $q_1 \neq 0$ or $q_2 \neq 0$                  |            |            | $q_1 \neq 0$ or $q_2 \neq 0$  |                            |          |                        |                    |
|                        | $q_1 = q_2 = 0$                               | $K = 1/3$  | $K = 3$    | $0 \leq K < 1/3$<br>$K = 1/4$ | $1/3 < K < 1$<br>$K = 1/2$ | $K = 1$  | $1 < K < 3$<br>$K = 2$ | $K > 3$<br>$K = 4$ |
| Cracking in mortar     | >0 (3.69)                                     | >0 (3.69)  | >0 (3.69)  | <2.542                        | >-1.271                    | >-0.318  | >-0.636                | <0.636             |
| Cracking synchronously | = 0 (3.69)                                    | = 0 (3.69) | = 0 (3.69) | = 2.542                       | = -1.271                   | = -0.318 | = -0.636               | = 0.636            |
| Cracking in rock       | <0 (3.69)                                     | <0 (3.69)  | <0 (3.69)  | >2.542                        | <-1.271                    | <-0.318  | <-0.636                | >0.636             |

The critical cracking model analysis of different medium materials shows that the cracking order of mortar layer and rock mass is depended on the mechanical properties of mortar and rock mass, in-situ stress and thickness of mortar layer. The cracking condition of different medium without considering the effect of in-situ stress is the same as that of different medium considering the effect of in-situ stress while  $K = 3$  or  $K = 1/3$ .

**Simulation results:**

**Model and parameters of example:** Model of example is established shown as Fig. 4. The diameter of bolt is 20 mm. The thickness of mortar layer is 5 mm which is the minimum value regulated by standard. The distance from the outer boundary of mortar layer to that of rock mass is 200 mm. The material parameters of mortar and rock are shown in Table 1. The coefficient relation to material and model shows in Table 2.

**Model and parameters of example:** Corresponding to parameters of mortar, rock, bolt and anchorage, the critical cracking conditions of different cracking model under different conditions are shown in Table 3, they can be obtained according to the formula above mentioned.

The Table 3 shows as follows:

- While without considering *in-situ* stress and  $K = 1/3$  or  $3$ , the formula  $\alpha^2 - (1 + \psi) t + (1 + \psi - \alpha)$  is 3.69, cracking condition in mortar layer is satisfied and the first crack appears in mortar layer during bolts rust expansion.
- The parameters  $q_0$ ,  $q_1$  and  $q_2$  are compressive stress, so the ratio  $q_1$  to  $q_0$  should be greater than zero for underground engineering. While the parameter  $K$  is greater than  $1/3$  and less than  $3$ , the first crack appears in mortar layer during bolt rust expansion. While the parameter  $K$  is greater than or equal to zero and less  $1/3$  or greater than  $3$ , three cracking models will be appeared under different stress ratios.

**CONCLUSION**

During the process of analyzing bolt rust expansion, the cracking model of anchor structure of

underground engineering under different stress ratios at the view of rust expansion stress is discussed. According to construction technology and simplifying rust expansion mechanical model of anchor structure of underground engineering and seeing the stress in surrounding rock mass caused by rust expansion stress as additional stress, the elastic criterion of different cracking model of anchor structure of underground engineering under different stress ratios is rewarded.

The critical cracking model analysis of different medium materials show that the cracking order of mortar layer and rock mass is depended on the mechanical properties of mortar and rock mass, in-situ stress and thickness of mortar layer. The cracking condition of different medium without considering the effect of in-situ stress is the same as that of different medium considering the effect of in-situ stress while  $K = 3$  or  $K = 1/3$ . And the analysis of example shows that three different cracking model could be appeared under different stress ratios.

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