# Study on the propagation of interface crack of young concrete lining and rock under blasting load

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**Abstract**: In the construction of water conservancy and hydropower project, young concrete lining structure is often affected by blasting load. Young concrete has a lot of micro-fractures with random distribution, which are easier to propagate and connect under blasting load. This paper focuses on the calculation on dynamic stress intensity factors of bond interface crack of concrete-rock according to concrete age. Result shows that different incidence angles of stress wave lead to different crack propagation mechanisms. Under the normal incidence of impact load, the bonding interface crack propagation of the concrete lining is mainly caused by reflection tensile stress, which forms from the free surface. With horizontal incidence of stress wave, the bond interface crack propagation of concrete lining is affected by concrete age. With the increase of concrete age, the elasticity modulus margin between concrete and rock decreases gradually, and the crack propagation form changes from shear failure to tensile damage.
**Key words**: young concrete lining; dynamic stress intensity factors; numerical calculation

## 1 Introduction

With economic development, many hydropower projects need urgent expansion of their power capacity. As a result, two parallel tunnels are often excavating simultaneously, or two adjacent tunnels are constructed one after another, or a new tunnel is under construction near a completed one. It is inevitable that the blasting excavation in construction will cause rock damage of its adjacent tunnels. The rock damage includes two situations: one is the influence of blasting vibration on the existing wall of the tunnel section; the other is the damage or even destruction of existing concrete lining by blasting vibration. At times, because of the constraints of the planned direction of the tunnel or the requirements of the project, the distance between the two adjacent tunnels is fairly short. For example, the pitch between Geheyan's four diversion tunnels is only one time that of the tunnel diameter; in addition, there are many cracks in the bond interface between rock and concrete structure due to the long-running load, and thus the cracks will further expand if there is blasting. Construction period will be prolonged and potential safety problems will be left if these problems are not solved well.

## 2 Fracture toughness and fracture criteria of bond interface of concrete-rock

### 2.1 Dynamic fracture toughness

Concrete is composed of three-phase medium: coarse aggregate, cement matrix, and the brittle layer formed at the junction between both. Generally, the thickness of the junction is 10 to 50 μm[1]. Li Zhe et al. from Xi'an University of Technology have experimented on the fracture criteria for interface cracks of rock and concrete[2-4]. Test results show that the fracture energy of rock and concrete interface is below that of concrete only; the interface fracture toughness of rock and concrete cracks is inferior to that of concrete as well. Fracture energy of rock and concrete interface is about 54.3 % of that of concrete, and the interface fracture toughness of the former is about 56.3 % of the latter. For mortar and concrete of equal intensity, the fracture energy and fracture toughness of the interface between rock-mortar and rock-concrete can be very close[3].

Concrete has different properties under different loading conditions, say, the static and the dynamic, which is largely up to the inner micro-structure of concrete. Researches show that dynamic fracture is 30 % tougher than static fracture[5]. Because the dynamic fracture toughness of concrete is in relation to loading change rate, its value is close to static fracture toughness in a low-frequency load. However, dynamic fracture toughness will be greatly increased with high-frequency. Considering the size effect of fracture toughness and for safety, dynamic fracture toughness value

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of large-volume concrete is 110 % that of the value of static; the rock-concrete interface fracture toughness value is about 56.3 % that of concrete fracture toughness, and thus the rock-concrete interface fracture toughness value can be obtained.

## 2.2 Fracture criteria

For the crack type with a combination of Ⅰ and Ⅱ, the stress formula in polar coordinates near crack tip is as follows[6]:

$$\left.\begin{aligned}\sigma_r &= \frac{1}{2\sqrt{2\pi r}}\left[K_{\mathrm{I}}(3-\cos\theta)\cos\frac{\theta}{2}+K_{\mathrm{II}}(3\cos\theta-1)\sin\frac{\theta}{2}\right]\\ \sigma_\theta &= \frac{1}{2\sqrt{2\pi r}}\cos\frac{\theta}{2}\left[K_{\mathrm{I}}(1+\cos\theta)-3K_{\mathrm{II}}\sin\theta\right]\\ \tau_{r\theta} &= \frac{1}{2\sqrt{2\pi r}}\cos\frac{\theta}{2}\left[K_{\mathrm{I}}\sin\theta+K_{\mathrm{II}}(3\cos\theta-1)\right]\end{aligned}\right\} \quad (1)$$

From Eq.(1) we can see that, since the stresses in polar coordinate tend to be infinity at $r = 0$, it is impossible to define the maximum of $\sigma_\theta$, and it is only available to compare the stresses $\sigma_\theta$ at the points around the circumference, which has a short distance to the top of crack. In this way, we can draw the extreme value of $\sigma_\theta$ and its location, and then find out crack angle $\theta_0$.

Crack propagation direction can be identified as follows

$$\left(\frac{\partial\sigma_\theta}{\partial\theta}\right)_{r=r_0} = 0, \quad \frac{\partial^2\sigma_\theta}{\partial\theta^2} < 0 \quad (2)$$

Put Eq.(1) in Eq.(2), the following result will come out:

$$\cos\frac{\theta_0}{2}\left[K_{\mathrm{I}}\sin\theta_0 + K_{\mathrm{II}}\left(3\cos\theta_0 - 1\right)\right] = 0 \quad (3)$$

The root $\theta = \pm\pi$ has no actual meaning, so crack angle $\theta_0$ is decided by Eq.(4)

$$K_{\mathrm{I}}\sin\theta_0 + K_{\mathrm{II}}(3\cos\theta_0 - 1) = 0 \quad (4)$$

If the maximum tangential tension stress in this direction $(\sigma_\theta)_{max}$ reaches critical value, the cracks begin to propagate, that is

$$\sigma_{\theta_0}\sqrt{2\pi r_0} = K_{\mathrm{IC}} \quad (5)$$

Put the above Eq.(5) into Eq.(1), we can get

$$\frac{1}{2}\cos\frac{\theta_0}{2}\left[K_{\mathrm{I}}\left(1+\cos\theta_0\right) - 3K_{\mathrm{II}}\sin\theta_0\right] = K_{\mathrm{IC}} \quad (6)$$

For dynamic fractures with a combination of Ⅰ and Ⅱ, the static fracture criterion mentioned above can be employed as crack initiation criterion. $K_{\mathrm{I}}$, $K_{\mathrm{II}}$ can be replaced by dynamic fracture factors, and $K_{\mathrm{IC}}$ by dynamic fracture toughness. For project fracture criteria, all the criteria mentioned above can meet the needs in production.

# 3 Bond interface crack propagation under blasting load

## 3.1 Calculation principle

At the crack tip, the stress of linear elastic uniform (not necessarily isotropic) medium under dynamic load has similar $r^{-1/2}$ singularity in bands with that of the static, which is not vulnerable to rapid load changes or fast crack propagation. As a result, dynamic stress intensity factor can be defined as[5]:

$$K_{\mathrm{I}}^{dyn}(t) = \lim_{r\to 0}\sqrt{2\pi r}\,\sigma_{yy}(r,0,t) \quad (7)$$

$r$ is the vertical distance between a point on the crack surface and the crack tip. $\sigma_{yy}$ is the stress perpendicular to the crack surface.

For the situation of stable crack with external load changes, analysis shows that the formula expression of crack-tip stress field and displacement field is similar to that with static load, that is,

$$\sigma_{ij} \propto 1/\sqrt{r}, \quad \sigma_i \propto \sqrt{r} \qquad i,j \text{ are } x,y$$

In plane strain, the formula for dynamic stress intensity factor by displacement method is as follows:

$$K_{\mathrm{I}}^{dyn}(t) = \frac{Eu_y}{4(1-v^2)}\sqrt{\frac{2\pi}{r}} \quad (8)$$

$K_{\mathrm{I}}^{dyn}(t)$ is the dynamic stress intensity factor defined by Eq.(7), $u_y$ is the displacement perpendicular to crack surface, and $E$ and $v$ is the elastic modulus and Poisson's ratio of the material respectively. Despite the difference in formula with static load, because the stress field and the displacement field are functions of time, there is essential difference between dynamic and static fields.

In this paper, the finite element program ANSYS is employed to calculate dynamic stress intensity factor. The value of $K_{\mathrm{I}}^{dyn}(t)$ in plane strain can be drawn through the dynamic opening displacement of crack tip in Eq.(8). Dynamic displacement field can be accessed through dynamic equations.

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{f\} \quad (9)$$

In this equation, $[M]$ is the overall quality matrix, $[C]$ is the damping matrix, $[K]$ is the overall stiffness matrix, and $\{\ddot{u}\}$, $\{\dot{u}\}$, $\{u\}$ are acceleration vector, velocity vector, and displacement vector of nodes respectively. $\{f\}$ is the equivalent nodal force vector.

The time numerical integration of dynamic equations has two main methods: center difference method and Newmark gradual integration method. ANSYS employs Newmark gradual integration method to get access to the dynamic equations. The basic idea is to make $t$ to meet the displacement vector $\boldsymbol{u}(t)$ in Eq.(9) at any time. According to Eq.(9), at $t+\Delta t$ moment, the following can be obtained based on dynamic equation:

$$[M]\{\ddot{u}_{t+\Delta t}\} + [C]\{\dot{u}_{t+\Delta t}\} + [K]\{u_{t+\Delta t}\} = \{f_{t+\Delta t}\} \quad (10)$$

Speed and displacement can be obtained by the following:

$$\{\dot{u}_{t+\Delta t}\} = \{\dot{u}_t\} + [(1-\alpha)\{\ddot{u}_{t+\Delta t}\} + \alpha\{\ddot{u}_{t+\Delta t}\}]\Delta t^2$$

$$0 \leqslant \alpha \leqslant 1 \quad (11)$$

$$\{u_{t+\Delta t}\} = \{u_t\} + \Delta t\{\dot{u}_t\} + [(\frac{1}{2}-\beta)\{\ddot{u}_t\} + \beta\{\ddot{u}_{t+\Delta t}\}]\Delta t^2$$

$$0 \leqslant 2\beta \leqslant 1 \quad (12)$$

Where, $\alpha$, $\beta$ are two parameters for controlling algorithm accuracy and stability. When $\alpha \geqslant 0.5$, $\beta \geqslant 0.25(0.5+\alpha)^2$, the algorithm is unconditionally stable. ANSYS can adjust the values of integral parameters $\alpha$ and $\beta$, and default value $\alpha = 0.5050$, and $\beta = 0.2525$. If initial displacement $\{u\}$ and initial velocity $\{\dot{u}\}$ are known, initial acceleration will be obtained by Eq.(9). Based on Eq.(10), Eq.(11) and Eq.(12), the displacement, velocity, acceleration can be calculated at the next moment, and then the displacement, velocity, acceleration values of discrete points at any time can be acquired and the stress and strain, stress intensity factor can all be obtained as well.

### 3.2 Numerical analysis model

Generally, cylindrical cartridge is used in blasting excavation, and cylindrical stress wave is produced near blasting hole, but within a certain distance from the explosion source, it can be considered as a plane wave.

To simplify the problem and for the convenience of research, suppose that there is crack between rock and concrete interface, and foundation rock and concrete are both homogeneous isotropic. The top of simulation model is free boundary, the left is symmetrical, the right is nonreflecting and the bottom adopts the load boundary. To save time and reduce work in calculation process, the adopted load is triangular[7], which is demonstrated in Fig. 1. Taking stress wave attenuation into consideration, stress wave shape is widened, load value is 1 MPa, load increase time is 200 μs and the total time is 1ms. The boundary and mesh division is shown in Fig. 2. To simulate the singularity of stress-strain field at crack tip, the 1/4 node element module around the crack tip is used, as shown in Fig. 3.

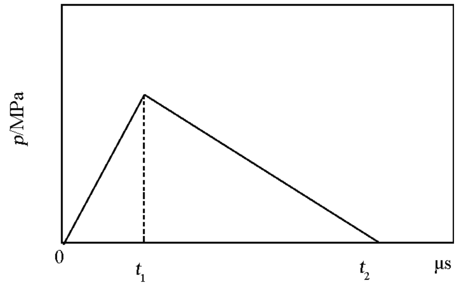


**Fig. 1 Blasting loading**

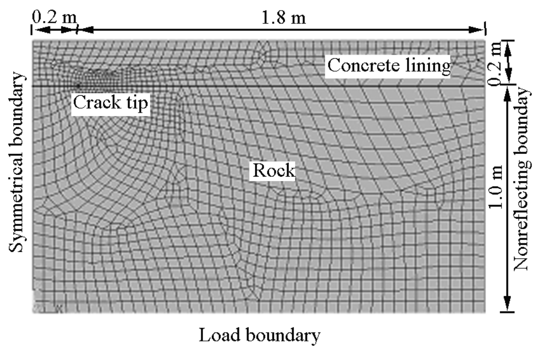


**Fig. 2 Finite element grids of the model**

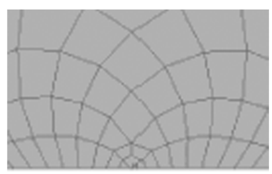

**Fig. 3 Singular element of crack-tip**

### 3.3 Rock and concrete mechanical parameters

The mechanical parameters of rock and concrete are important factors influencing young pouring concrete under blasting vibration load. To make sure of the influence of mechanical parameters to rock, the actual parameters are referenced. Rock mechanical parameters is as follows[8]: the density is 2 700 kg·m$^{-3}$, the dynamic elastic modulus is 30 GPa and the poisson's ratio is 0.2.

The mechanical properties of concrete are closely related to its age, so the four-age of the concrete is considered to analyze the dynamic response in calculation process. Mechanical parameters of concrete of each age are shown in the table below:

**Table 1 Material parameters of concrete**

| Age/d | Density/ (kg· m$^{-3}$) | Elastic modulus/ GPa | Poisson's ratio | dynamic fracture toughness of bond interface of concrete-rock / (MPa· m$^{1/2}$) |
|---|---|---|---|---|
| 1 | 2 450 | 7 | 0.2 | 0.21 |
| 3 | 2 450 | 13 | 0.2 | 0.36 |
| 7 | 2 450 | 20 | 0.2 | 0.5 |
| 28 | 2 450 | 30 | 0.2 | 0.65 |

## 3.4 Results and analysis

At stress wave vertical incidence circumstances, the dynamic stress intensity factor curve of various age concrete are shown from Fig. 4 to Fig. 7. Elasticity modulus of rock is 30 GPa.

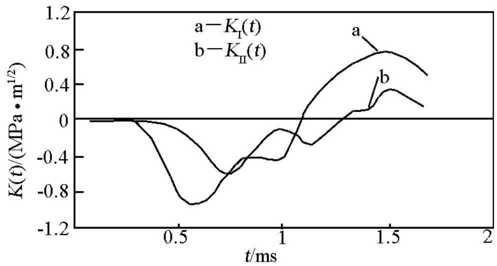


**Fig. 4 Dynamic stress intensity factor curves of concrete interface crack (1 day)**

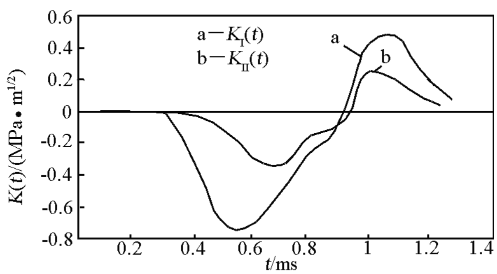


**Fig. 5 Dynamic stress intensity factor curves of oncrete interface crack (3 day)**

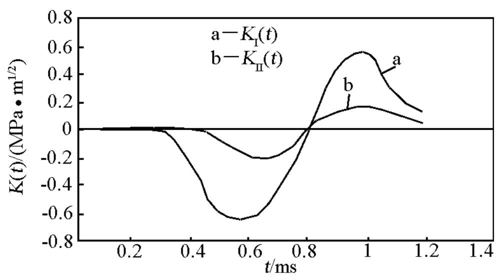


**Fig. 6 Dynamic stress intensity factor curves of concrete interface crack (7 day)**

Result shows that: firstly, the crack is compressed and close because of the vertical incidence of stress wave, and then it will be in the tension-shear state with tensile stress by stress wave formed by reflection on free surface. The dynamic stress intensity factor

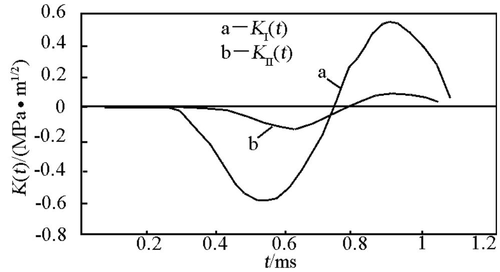


**Fig. 7 Dynamic stress intensity factor curves of concrete interface crack (28 day)**

of crack tip $K_I(t)$ is greater than that of $K_{II}(t)$, so crack propagation is mainly caused by the tensile stress.

With the increase of concrete age and elastic modulus, the elastic modulus margin between concrete and rock gradually decreases, so do the peaks of the dynamic stress intensity factor of crack tips $K_I(t)$ and $K_{II}(t)$. When the ratio of the elasticity modulus between concrete and rock is 1, the peak of $K_I(t)$ is 0.55 MPa· m$^{1/2}$, and the peak of $K_{II}(t)$ is 0.12 MPa· m$^{1/2}$. Based on the fracture criteria of maximum tensile stress, the bond interface crack of one-day concrete begin to propagate at the time of 1.3 ms, and the initiation angle is 8°; the bond interface crack of three-day to seven-day concrete begin to propagate at the time of 1.0 ms, and the initiation angle is 18°, while the bond interface crack of 28 day concrete is not damaged. Result shows that with vertical incidence of blasting load, the bond interface crack propagation of the concrete lining is mainly caused by reflection tensile stress forming on free surface. With the increase of concrete age, the strength of blasting load should be further increased to cause crack propagation.

When stress wave is horizontal incidence, the dynamic stress intensity factor curve of various age concrete are shown from Fig. 8 to Fig. 11. Elasticity modulus of rock is 30 GPa.

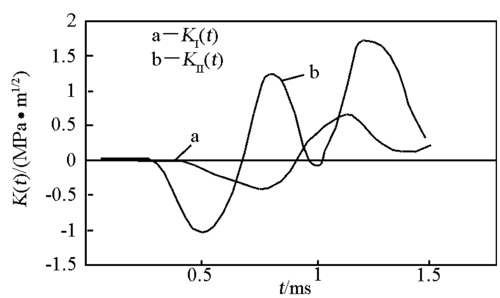


**Fig. 8 Dynamic stress intensity factor curves of concrete interface crack (1 day)**

Result shows that: when stress wave is horizontal incidence and the concrete is one-day old, crack prop-

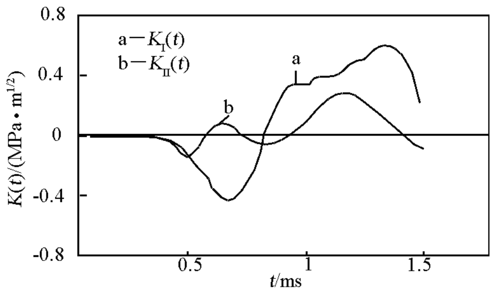


**Fig. 9 Dynamic stress intensity factor curves of concrete interface crack (3 day)**

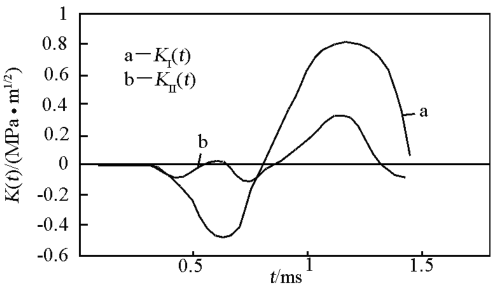


**Fig. 10 Dynamic stress intensity factor curves of concrete interface crack (7 day)**

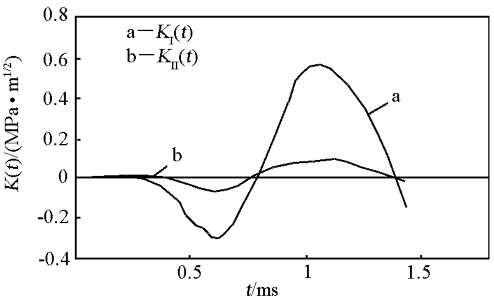


**Fig. 11 Dynamic stress intensity factor curves of concrete interface crack (28 day)**

**agation are mainly caused by shear stress because of the great elastic modulus margin between concrete and rock; with the increase of the age, the elastic modulus** margin gradually decreases, crack propagation is caused by tensile stress. The dynamic stress intensity factor of crack tip $K_I(t)$ is greater than that of $K_{II}(t)$, so crack propagation is mainly caused by the tensile stress. When concrete is the same age, the calculation of dynamic stress intensity factor $K_I(t)$ with stress wave of horizontal incidence is greater than that of vertical incidence, and the sustaining time is longer, so cracks are easier to propagate when stress wave is with horizontal incidence.

## 4 Conclusions

Conclusions can be drawn through analyzing dynamic stress intensity factor of bond interface cracks between concrete lining and rock.

1) With vertical incidence of stress wave, the bond interface crack propagation of concrete lining is mainly caused by tensile stress of reflection formed on free surface.

2) With horizontal incidence of stress wave, the bond interface crack propagation of concrete lining is affected by concrete age. With the increase of concrete age, the elasticity modulus margin between concrete and rock decreases gradually, and the crack propagation form changes from shear failure to tensile damage.

### References

[1] Kcaoglu T, Tokyay M, Celik T. Effect of coarse aggregate size on the interfacial cracking under uniaxial compression [J]. Materials Letters, 2002, 57: 828-833.

[2] Li Zhe, Liu Maoshe, Zhang Jianshan Experimental study on fracture criterion of rock-concrete interface and breaking energy[J]. Journal of Shanxiwater Power, 2001, 17(4): 35-37. (in Chinese)

[3] Li Zhe, Yang Shuicheng, Zhang Haobo. Fracture toughness and breaking energy of rock-concrete interface[J]. Water Resources & Water Engineering, 1998,9(1): 42-45. (in Chinese)

[4] Li Zhe, Zhang Haobo, Jian Zheng. Study on fracture criterion of rock-concrete interface[J]. Journal of Dalian University of Technology, 1997, 37(Supp.1): 57-60. (in Chinese)

[5] Fan Tianyou. Principles and Applications of Dynamic fracture [M]. Beijing: Beijing Institute of Technology Press, 2006. (in Chinese)

[6] Yin Shuangzeng. The Application of Fracture Criteria in Concrete Project[M]. Beijing: Science Press, 1996.

[7] Wu Liang, Lu Wenbo. The Analysis of dynamic stress intensity Factors of rock under pre-split blasting loading[J]. Rock and Soil Mechanics,2007, 27(S2): 791-794. (in Chinese)

[8] Chen Ming. Study on the Influence of Blasting Vibration upon Freshly Placed Concrete Structure[D]. Wuhan: Wuhan University,2006. (in Chinese)

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