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Numerical Simulation Study on Expansion of the Crack and Energy Variation Status in the Process of the Projectile Penetration of Concrete

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***Abstract*—Based on the discrete element software PFC2D, building background grid model of concrete under simulated different projectile penetration rate, in the process of penetration of concrete target, the expansion of the crack damage, and compared with the cement mortar model. In crushing zone near the projectile formation, in away from the projectile as the big crack area, cement mortar in the move away from the projectile distribution is symmetrical, mainly along the coarse aggregate and cement mortar and concrete crack of interface to conduct; To monitor the energy conversion in the process of projectile penetration, further combining with the energy dissipation structure it was pointed out that the essence of the penetration process of damage is caused by the energy dissipation of driven by energy release of a state instability phenomenon, is a combination of energy release and energy dissipation is the internal cause of penetration gradual damage.**

Keywords-penetration; stress propagation; expansion of the crack; energy variation; numerical simulation

I. INTRODUCTION

The penetration problem of projectile into target has a long history and has experienced a long process of exploration with the development and progress of human society. Because of the natural contact between penetration and military field, since the beginning of nineteenth Century, people have made unremitting research, such as armor penetration, the damage on buildings of kinetic energy bomb, Safety calculation and evaluation of protection engineering, etc.

The penetration process of concrete targets is extremely complex, which involves many mechanical behaviors of projectile materials and target materials. Relevant scholars at home and abroad have made a lot of research on the penetration problem. Zhao Guozhi with other experts did numerical simulation analysis on extending penetrator penetrating into finite target and semi-infinite target with attack angle by using LS-DYNA, and made comparison between those two targets from the angle of the kinetic energy of the target and penetration ability of the reference rod with the same mass and outside diameter. Forrestal and Luk applied the theory to analyze the depth and acceleration of the projectile penetrating into the soil; Satapathy and other scholars also applied the theory in the study of metal and ceramic target penetration.

Mainly focused on experimental research and analysis on macroscopic laws, most of the research on the dynamic fracture process and mechanism are still not enough. It is very rare to study the penetration problem from the perspective of meso damage evolution. In the meso structure, generation, expansion, instability and the failure process of the micro cracks can explain the mechanism of the macroscopic mechanical behavior of concrete materials. When concrete is subjected to dynamic loads, the dynamic mechanical behavior of concrete is completely different from that of the static state in the failure process and energy dissipation mechanism. Therefore, it is significant to develop a dynamic meso scale model, which has important significance for the study of the heterogeneity and dynamic failure process of meso structure. Therefore, it is significant to develop a dynamic meso scale model for the study of the heterogeneity and dynamic failure process of meso structure.

II. THE ESTABLISHMENT OF PFC2D MODEL

A. The Basic Principle of PFC2D

In the micro system, many micro factors influence the expression of the macroscopic mechanical properties of rock to a certain extent, and the operation mechanism of PFC under external load can be summarized as follows: Particle motion law→the relative motion of the contact force and torque→whether the contact force to make the bond fracture. As shown in Figure 1, the movement of particles is correlative with effect of resultant and resultant moment. The resultant Fi makes the particles exhibit translational motion, and the resultant force moment Mi enables the particles to exhibit rotational motion. The form of motion of a particle is different from that of another particle (relative displacement relation). Force and moment would be emerged from the interface of two particles, that is to say, relationship between force and displacement of particles. The parallel bond model represents a cemented medium with a certain volume between the particles, which can bear the function of force and torque at the same time. The calculation formula, which of the maximum normal tensile stress and tangential stress from force and moment distributing in the bond medium, should be:

$$\left.\begin{aligned} \sigma_{\max} &= \frac{-\overline{F}_i^{\mathrm{n}}}{A} + \frac{|\overline{M}_i^{s}|}{I}\overline{R} \\ \tau_{\max} &= \frac{|\overline{F}_i^{s}|}{A} + \frac{|\overline{M}_i^{\mathrm{n}}|}{J}\overline{R} \end{aligned}\right\} \quad (1)$$

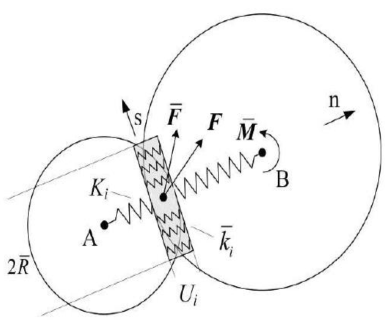

Figure 1. Parallel connection model of particle element

In the calculation formula, A is the cut area of bond medium, J and I are respectively the polar moment of inertia and the moment of inertia, the R is the equivalent radius, and N and S respectively represent normal and tangential direction.

B. The Pretreatment of the Model and the Parameter Inversion

In order to analyze and study the mechanical properties of concrete at the mesoscopic level, the concrete is considered as an inhomogeneous material consisting of aggregate, mortar and interface. The establishment of the meso mechanical model of the concrete granular elements mainly consists of two steps: the fine view pretreatment method and the inversion of the meso parameters. The steps to determine the meso parameters are as follows:

(1) According to the size of the beam specimen and the minimum size of aggregate, we determine the particle unit radius R of the model, whose size distribution is generally in a certain range of random generation, and meet the Gauss distribution. Particle density is calculated by the density and porosity of concrete material model, and coefficient of friction μ between particles is determined.

(2) Elastic modulus ratio and strength ratio of aggregate, mortar and interface were assumed. For example, according to the tensile test results of the three groups, we fixed that Ea: Ec: Ei = 2.4:2:1, the subscripts of which represent aggregate, mortar and interface respectively.

(3) By the relationship between the kn/ks and Poisson's ratio, the inversion of each component kn/ks

(4) According to the test of the concrete elastic modulus E, the inversion is obtained with the stiffness of kn and ks.

It is necessary to point out that in the dynamic analysis, in order to make the energy dissipation process reflect the actual situation better, the local damping of the concrete target is set to zero, and the viscous damping is activated. The related parameters of the missile body, coarse aggregate and fine aggregate are obtained by simulation experiment.

C. Model Generation

As shown in Figure 2, in the concrete target discrete element model, the concrete coarse aggregate is put with background-mesh methods; the fine aggregate is replaced by a single particle and the particles of cementing material is connected in the way of the parallel connection. Target plate model size is 1600mm * 800mm. The pointed projectile reaches a length of 150mm, diameter 25mm. The mixture of a concrete model is composed of 6142 particles.

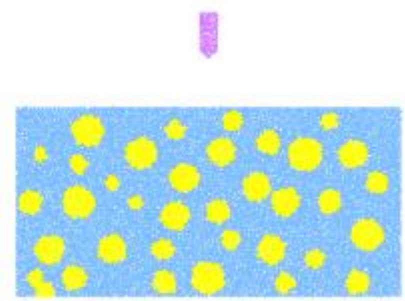

Figure 2. Concrete penetration model

III. ANALYSIS OF CONCRETE PENETRATION PROCESS

A. Simulation Result Analysis

As shown in Figure 3, 4, 5 and 6, the simulation applies different projectile penetration rate - 240m/s, 200m/s and 160m/s respectively. After observing the concrete target after simulation test, we find that penetration stress is spread out in the form of spherical wave after the projectile hit the concrete barrier (Due to the complexity of spherical wave, the practical processing is generally simplified as plane wave when considering) as figure 3. The stress causes the material to be compressed and the shear deformation, thus the surface cracks and penetration funnel is obviously formed around the projectile on the surface of concrete, which makes the concrete into powder. In the concrete, the free surface of the target is formed by the tension zone, which leads to the expansion of the rock mass. When the tensile strength is greater than the extensional stress of rock, concrete will crack and broken and become block.

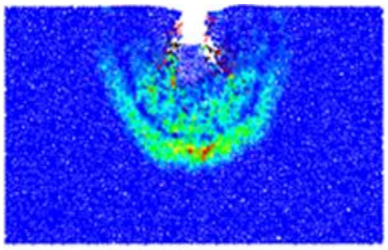

Figure 3. Penetration stress wave propagation process

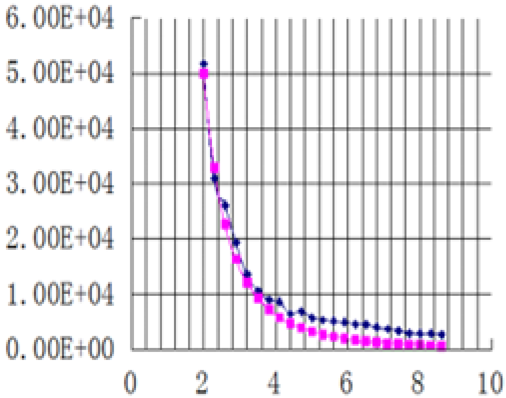

Figure 4. Comparison of stress wave propagation process

Different projectile penetration rate will lead to different target plate damage mechanism. In Figure 5, when the projectile velocity is relatively large, due to the reverse tension pulse of penetration stress wave, once some dynamic fracture criterion of the concrete is met, the formation of the rock mass is broken, so that a new free surface is formed at the fracture. The incident pressure wave will be reflected on this new free surface, which will result in second layers of cracks, and so on. Multilayer crack can be formed under certain conditions. In Figure 6, when the projectile velocity is relatively small, due to the smaller stress wave back tension, the concrete target plate cannot be cracked. Therefore it is only partial depression and overall bending of concrete. Overall speaking, the greater the projectile penetration rate is, the greater diameter and depth of the penetration funnel formed at the entrance are, and the easier to be destroyed the concrete target is.

It can be seen from the figure that when the bullet penetrate into the target with high speed, it produces a stronger stress wave in the target, which obviously has greater damage to the target. After the test, there are several radial cracks in the front of the concrete target plate and develop in the direction of the four corners of reinforced concrete target. Some cracks extend to the edge of the target plate. For the existence of combined cracks in the concrete target plate, when the bullet hit the concrete target, the crack starts to expand under the tangential tensile stress generated in the concrete target plate. With the continued penetration of the bullet, the crack will be further expanded and extended to produce a number of radial cracks in the concrete target. The stress wave generated by the high stress zone around the bullet head is propagated in the target plate and reflected to the tensile stress on the free surface of the target plate, which leads to the tensile failure of the target material. The compressive stress wave generated in the target plate is transferred by the corner of the intersection of two free surfaces. The unloading tensile waves reflected by the two free surface meet in the concrete target and forms tensile stress, which produces radial cracks in the direction of the four corners of reinforced concrete target.

As can be seen from Figure 7, the weak points of concrete strength exist in the rough aggregate and cement mortar at the junction. Due to the concentration of stress at the cementation surface, on large crack area far from the projectile, the crack propagation is always carried out at the interface between the cement mortar and the coarse aggregate. The crack of simple penetration of cement mortar block is roughly symmetrical distribution. The crack of concrete test block is mainly related to the distribution of coarse aggregate.

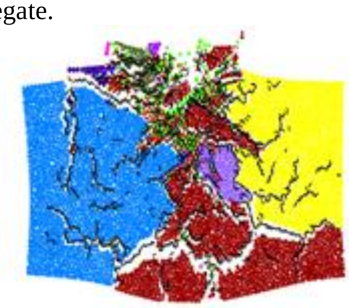

Figure 5. 240m/s of projectile penetration rate

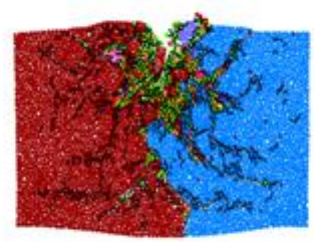

Figure 6. 160m/s of projectile penetration rate

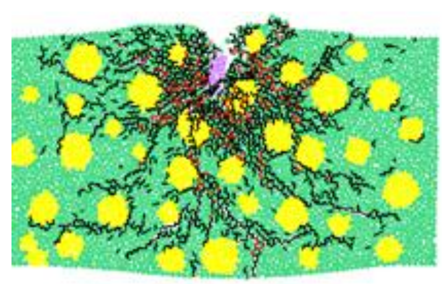

Figure 7. Crack propagation in concrete penetration process

B. Energy Analysis of Penetration Process

Because the projectile penetrating concrete is instantaneous, from the point of view of energy change, the concrete penetration process is different from the conventional three axis test. We divide the failure process into four stages. As shown in Figure 8, the energy change curve of penetration process can be divided into two sections. The dissipation energy of the crack growth phase (OA) increases dramatically (damping and sliding), the growth rate of the elastic energy becomes slow, and the maximum value is reached at the peak.

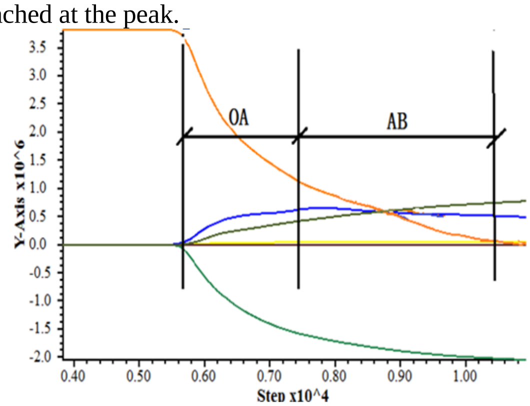

Figure 8. Energy change curve of penetration process

At the beginning of the projectile penetration, the elastic energy begins to aggregate, and releases rapidly after reaching the peak. This process is a continuous process of change; it is bound to have the maximum value of the elastic storage. The faster the projectile velocity, the more quickly the concrete elastic energy storage can reach its ultimate elastic properties, but the limit storage energy is not affected by the velocity of the projectile.

The elastic potential energy stored in particle is depleted by friction and damping effect in the process of damaged surface formation. The other part will transfer to strain energy of jointed rock mass, which makes elastic potential energy of particles fluctuate in the range of damage surface. Since the elastic potential energy system always back to the average value, the elastic potential energy will be released immediately, resulting in the formation of new damage surface.

In the whole process of penetration, the kinetic energy of the projectile is continuously transformed into the elastic potential energy of the concrete target, and the dissipation of the elastic potential energy is also existed. The interface is in a dynamic state of balance. The overall reserve of elastic potential energy is larger than that of friction and damping before the crack is not penetrated by concrete, which is increasing at that time. When the elastic potential energy reaches the peak value, it releases rapidly. Then the concrete is destroyed, and the macroscopic breakthrough surface occurs. Thus, under the combined effect of energy dissipation and release, deterioration and loss of strength show up in the weak surface of concrete target. It can be seen that the generation and development of the damage surface is caused by the energy dissipation driven by the energy release.

IV. CONCLUSION

(1) Meso mechanics of concrete is the mechanism analysis of macroscopic mechanical phenomena from the aspect of material at the failure level of meso scale. The failure process of concrete is mainly for the initiation and propagation of micro cracks, and the process of the formation of macroscopic cracks on the meso scale, and damage-crack-destruction process on the macro scale. Mechanism of damage localization and strain softening of concrete can be explained by using simulation of mechanical behavior of concrete by meso mechanical model.

(2) The penetration process is transient; the energy evolution process is mainly divided into two stages, the crack growth stage and the post peak failure stage. In the stage of crack growth, the continuous "compensation" is the intrinsic factor of crack propagation after energy dissipation, and the generation and development of the damaged surface is caused by the energy dissipation driven by the energy release. When the accumulation of elastic potential energy reaches the upper limit, it enters the stage of post peak failure.

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