Dynamic properties and fracture damage characteristics of granite under impact load

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Abstract. The goal of this research is to study the dynamic properties and fracture damage laws of granite at the meso-scale under impact load. The quasi-static and dynamic mechanical properties of granite were studied through laboratory tests (Uniaxial compression, split Hopkinson pressure bar). The establishment of three-dimensional coupled numerical model of rock specimen and split Hopkinson pressure bar was realized by new coupling technology of PFC-FLAC. Three wave superposition and end stress distribution were discussed to determine the stress balance of the specimen during the loading process. The dynamic compression mechanics response characteristics and crack growth laws of granite under different strain rates were studied. The results indicated that PFC-FLAC coupling technology can solve the problems of tedious modeling process and long calculation time in the past three-dimensional discrete element model, and can better describe the dynamic mechanical behaviour of rock. There is obvious rate dependency in the dynamic strength of rock material, and the dynamic compressive strength of rock increases with the increase of strain rate. The macro fracture of rock mass is the result of the continuous development, expansion, aggregation and connection of the internal microcracks. With the increase of strain rate, the increase and cross propagation of cracks lead transformation of rock from intact to crushing destruction. Under dynamic loading, the failure process of rock is crack initiation, propagation, crossing, transfixion and rupture.

1. Introduction

As shallow resources dwindle, more and more projects are moving deeper into the earth, such as oil, gas, and coal extraction, geothermal, tunnels, and nuclear waste storage. These deep projects are often accompanied by high in-situ stress, which will bring different degrees of disturbance when the construction is carried out, resulting in different forms of disasters such as rock burst, earthquake, collapse and so on [1]. Split Hopkinson pressure bars (SHPB) were initially used to study the dynamic characteristics of metal materials [2], and later developed to be mainly used for the dynamic characteristics of brittle materials such as rock and concrete [3-5]. On this basis, many scholars have done extensive research and produced a large number of researches. Hakalehto [6] studied the dynamic mechanical properties of granite, sandstone and marble, and the results showed that the crack initiation strength of the rock did not have obvious rate correlation, while the dynamic yield strength was about 2 times of the quasi static yield strength. Olsson et al. [7] and Cirne et al. [8] obtained a high strain rate constitutive model of tuff through SHPB impact tests. Lundberg [9] used the SHPB experimental device to study the broken state of rock under the action of stress wave, and found that under the action of impact load,
the crack of rock expands along the axial direction, and with the increase of dynamic load, the broken degree of crack also increases, and the broken rock specimen is in the form of symmetrical cone failure. However, due to the limitations of experimental technologies, many current damage measurement technologies, such as acoustic emission, acoustic wave, CT scan, etc., are still difficult to be applied to the real-time damage measurement of rock in dynamic impact tests [10-12]. With the development of computer technology, numerical simulation has effectively solved this problem, which can more easily reveal the details of stress and deformation at the microscopic level [13-14]. Discrete element software (PFC) has been used by many scholars to simulate rock fracture under different conditions due to its advantages in crack propagation and meso-damage [15-18]. But, due to the limits of computer hardware, which is limited to small range and plane model calculation, for example, the traditional SHPB discrete element numerical simulation, the incident bar, Transmission bar, and specimen are made up of many particles disc, which will take a long time to construct modulus and calculation. Therefore, it is still a difficult problem to perform large-scale three-dimensional discrete element model calculations.

In order to solve these problems, this paper aims to study the loading process of SHPB through continuous-discrete model, and verify its validity in the calculation of three-dimensional SHPB model. Firstly, the principle of SHPB technology was discussed, and a three-dimensional SHPB model was established based on PFC-FLAC coupling method. The specimen of particle based discrete element model was calibrated by static uniaxial compression test. Then, the validity of the model was analyzed by testing one-dimensional stress wave propagation and stress uniformity in a single bar. Finally, the micro-model was used to restore the fracturing process under dynamic loading, and the deformation law and dynamic damage evolution characteristics of specimen under different peak stress loading were discussed, which provided ideas for subsequent numerical simulation calculation under different conditions on the basis of 3D SHPB model.

2. Establishment and calibration of SHPB model based on PFC-FLAC

2.1. Fundamental principles of SHPB
A typical SHPB laboratory test consists of an impact bar, an incident bar, a transmission bar, a damping structure, and a test specimen sandwiched between the incident bar and the transmission bar. In the physical experiment, the impact bar impacts the incident bar along the axial direction at a certain speed, and the compression stress wave is generated in the incident bar. It is assumed that only elastic deformation occurs in the incident and transmission bars and the stress wave propagates in one dimension. When the stress wave reaches the specimen, if the wave impedance of the specimen is less than the wave impedance of the pressure bar, a reflected wave will be returned to the incident bar, and a wave transmitted through the specimen into the transmission bar. The pulse signal in the pressure bar is measured by the strain gage, the strain gage on the surface of the incident bar measures the incident and reflected signals, and the strain gage on the surface of the transmission bar measures the transmitted signals.

The validity of SHPB test is based on two basic assumptions: stress uniformity and one-dimensional stress wave propagation. The purpose of stress uniformity is to realize the quasi-static loading of the specimen. The "three-wave method" was used to process the data, and the stress $\sigma$, strain rate $\dot{\varepsilon}$, and strain $\varepsilon$ of the specimen were calculated by the strain signal $\varepsilon_{\text{in}}(t)$, $\varepsilon_{\text{re}}(t)$, $\varepsilon_{\text{tr}}(t)$ on the incident and transmission bars.

$$\sigma = \frac{E_{\text{bar}} A_{\text{bar}} (\varepsilon_{\text{in}} + \varepsilon_{\text{re}} + \varepsilon_{\text{tr}})}{2 A_{\text{spec}}} \quad (1)$$

$$\dot{\varepsilon}_{\text{r}} = C_{\text{bar}} \frac{\varepsilon_{\text{in}} - \varepsilon_{\text{re}} - \varepsilon_{\text{tr}}}{L_{\text{spec}}} \quad (2)$$
\[ \varepsilon_s = \frac{C_{\text{bar}}}{L_{\text{spc}}} \int_0^t (\varepsilon_{\text{in}} - \varepsilon_{\text{re}} - \varepsilon_u) \, dt \]

Where, \( E_{\text{bar}} \), \( C_{\text{bar}} \), \( A_{\text{bar}} \) are the elastic modulus, compressional wave velocity, cross-sectional area of the bar, respectively. \( A_{\text{spc}} \), \( L_{\text{spc}} \) are the cross-sectional area, length of the specimen, respectively.

2.2. Establishment of SHPB model

2.2.1. Introduction to PFC-FLAC coupling methods. The PFC-FLAC coupling scheme allows continuum and DEM model components to exist simultaneously in one instance, making it possible to study microstructure evolution and macroscopic mechanical response [19-21]. In PFC-FLAC coupling scheme, model based on FLAC area boundary composed of a certain number of triangle surface grid coupling boundary wall, each triangle vertex speed, position is considered to be a function of time, and then using the centre of gravity interpolation, the equal potency at each node of the triangle can be converted into the contact force and moment between the wall and the particle. In each cycle, the results (velocity and position) calculated by the FLAC model are transferred to the coupled boundary wall through the nodes, and then transferred to the PFC particles through the position change of the coupled boundary wall. Meanwhile, the contact force generated by the PFC particles and the boundary wall is sent back to the FLAC model through the nodes. The above process is repeated in each calculation step. PFC-FLAC coupling simulation is realized.

2.2.2. Bar system modeling. In order to ensure the accuracy of the results, the length of the incident bar should ensure that the stress wave can be reflected 9~10 times in the specimen. At the same time, the length of the incident bar and the transmission bar should ensure that the reflected wave generated by the initial reflected wave and the transmitted wave at the corresponding end face will not affect the stress balance of the specimen. Therefore, the lengths of the incident bar and the transmission bar in the model are set as 2.0 m and 2.0 m respectively, and the diameters are both 50 mm (see Figure 1a). See Table 1 for the specific parameters of the bar. The simulation process is set to stop the numerical calculation before the tensile wave generated at the end of the transmission bar reaches the specimen, thus eliminating the modeling process of the absorption device. In order to monitor the propagation process of stress wave in the numerical test, monitoring points are set on the incident bar and the middle part of the transmission bar respectively.

**Table 1. Physical parameter table of bar**

| Density (kg/m\(^3\)) | Poisson's ratio | Young's modulus (GPa) |
|----------------------|----------------|----------------------|
| 7850                 | 0.30           | 210                  |

2.2.3. Particle Specimen Modeling. According to ISRM suggested method, indoor uniaxial compression tests of granite were carried out, and the average values of experimental results are shown in Table 2. Then, according to the laboratory test, a standard cylindrical particle model of \( \phi 50 \) mm\(^{3} \) 100 mm was established, and the parallel bonding model (PBM) was used between particles. The model was in close contact with the force balance by servo preloading, and then the load was carried out by relative displacement of the two loading plates (the loading speed was 0.0025m/s). Until the load stops at 70% of the peak stress. The physical and mechanical parameters of granite obtained through laboratory experiments (such as uniaxial compressive strength, elastic modulus, Poisson's ratio, etc.) cannot be directly applied to the PFC3D numerical model. We need to repeatedly adjust the meso-parameters of the numerical model to make the macro results obtained from numerical simulation match the actual experimental results as much as possible. Finally, the results of model revision and model mesoscopic parameters are shown in Table 2 and Table 3. Considering the scale effect of the specimen and the ratio of macroscopic and mesoscopic parameters, the specimen size of
SHPB was selected as 25 mm × φ 50 mm (see Figure 1b), and the particle number of the model was 3228. The mesoscopic contact parameters were assigned according to the calibration results, in which the linearpbond contact model was adopted for ball-ball contact. Ball-facet adopts linear contact model. In order to monitor the stress and strain of the specimen, six measuring balls are arranged in the specimen (see Figure 1c).

**Table 2. Physical parameter table of bar**

|                      | Young's modulus (GPa) | Poisson's ratio | UCS (MPa) |
|----------------------|-----------------------|----------------|-----------|
| Experimental results | 36.89                 | 0.23           | 115.78    |
| Numerical simulation | 36.94                 | 0.23           | 115.42    |

**Table 3. Mesoscopic parameters of granite model**

| Particle             |                      |                |           |
|----------------------|----------------------|----------------|-----------|
| Minimum radius, $R_{\text{min}}$ (mm) | 1.0                  |                |           |
| Radius ratio, $R_{\text{max}} / R_{\text{min}}$ | 1.66                 |                |           |
| Density, $\rho$ (kg/m$^3$) | 2540                 |                |           |
| Young Modulus, $E_{\text{ball}}$ (GPa) | 36.60                |                |           |
| Friction coefficient, $\mu$ | 0.577                |                |           |

| Contacts              |                      |                |           |
|-----------------------|----------------------|----------------|-----------|
| Parallel Young modulus, $E_{\parallel}$ (GPa) | 36.60                |                |           |
| Parallel stiffness ratio, $k_{\parallel} / k_{\parallel}$ | 2.8                  |                |           |
| Parallel gap, (mm)    | 0.025                |                |           |
| Parallel Friction angle, $\Phi$ (degree) | 30                   |                |           |
| Parallel Cohesion strength, $c$ (MPa) | 70                   |                |           |
| Parallel Tension strength, $\sigma_{\parallel}$ (MPa) | 70                   |                |           |
| Linear Young modulus, $E_{\parallel}$ (GPa) | 36.60                |                |           |
| Linear stiffness ratio, $k_{\parallel} / k_{\parallel}$ | 2.8                  |                |           |

**Figure 1.** The continuous-discrete element model of SHPB. (a) Overall Diagram of the Model; (b) Local Diagram of Model; (c) The monitoring ball arrangement of the specimen
2.3. Verification of 3D SHPB model

2.3.1. Simulation of one-dimensional wave propagation on a bar. The revised model of the bar is shown in Figure 2. The monitoring points are installed at 0, 1, 1.5 and 2m respectively, and then a half-sinusoidal stress wave (peak stress of 200 MPa and loading period of 200 μs) is applied to one end of a single guided wave bar. According to the cloud map of the unbalance force of all sides of the whole bar during the loading process, it is found that the unbalance force in Y and Z directions is zero, and no obvious oscillation occurs along the direction of wave propagation. The lateral inertial forces on the neutral axis can be ignored, which ensures the one-dimensional wave propagation in the bar. According to the results of each monitoring point, the half sine wave can be correctly loaded, propagated and reflected in the bar.

![Figure 2](image)

Figure 2. (a) Schematic diagram of monitoring point layout;(b) Cloud image of unbalance force in all directions of the member (X,Y,Z in order);(c) Half sinusoidal stress wave pattern at different monitoring points

2.3.2. Verification of stress equilibrium of model specimen. The stress uniformity at both ends of the specimen is the key factor for the validity of SHPB test. As the stress wave is reflected back and forth between the end of the incident bar and the transmission bar, the stress distribution inside the specimen gradually becomes uniform. When the stress difference of the specimen decreases to a certain extent, the stress distribution of the specimen reaches approximately uniform. At this time, the stress state of the specimen is essentially quasi-static loading. Two methods, three wave method and end stress state method, are generally used to test the stress uniformity of the specimen. The three-wave test is to evaluate the macroscopic equilibrium state of the specimen by studying the magnitude of the unbalance force through the superposition of stress waves. As shown in Fig. 3(a) (for example, the loading period is 200 and the peak stress is 150MPa; A, B, and S are the incident wave, reflected wave and transmitted wave respectively). By translating the reflected wave and transmitted wave, the unbalanced stress of the specimen can be obtained. Unbalanced stress changes within a smaller volatility (the maximum unbalanced stress is 6.06 MPa), at the same time after the incident
wave and reflected wave superposition with specimen of stress wave and transmission wave are a good match, thus the specimen of the macroscopic equilibrium condition is satisfied, therefore using three wave method and wave method to calculate the accuracy can be compared. Another method of stress state at the end is to measure the force at the end of the specimen at the same time. This method studies the local equilibrium state of the specimen. Therefore, in the simulated SHPB test, the contact stress changes of the wall at both ends of the specimen were monitored in real time by the FISH language custom function, and then the stress balance factor \( \eta = 2(\sigma_{xx}^{in} - \sigma_{xx}^{uv}) / (\sigma_{xx}^{in} + \sigma_{xx}^{uv}) \) was used to describe the stress balance at both ends of the specimen, as shown in Fig. 3(b). After the stress wave reaches the incident end of the specimen, the stress at the incident end of the specimen increases and propagates to the transmitted end. When the stress wave reaches the transmission end of the specimen, the transmission occurs at the transmission end and the reflected stress wave propagates to the incident end. In this stage, the stress wave in the specimen at the incident end and the transmission end of the reflection constantly, the stress balance factor gradually decreases and tends to 0. When the stress balance factor reaches 0 for the first time, the stress reaches the peak at both ends of the specimen. During the whole process, the fluctuation of the stress balance factor is relatively slow, indicating that the specimen reaches a stable stress balance state. After the peak stress, stress balance factor can still remain at zero, but fluctuates significantly stronger than last time, when the stress is close to 0 MPa, while the stress difference between the two ends gradually decreases, but the ratio is opposite bigger, showing the stress balance factor fluctuates violently. The change of the stress balance factor during this period shows that the sample is not damaged in the post-peak stage and can still bear the stress load as a whole. The subsequent increase of the stress balance factor indicates that the incident end of the specimen has been separated from the incident bar, the stress at the incident end is zero, and some particles at the transmission end are still in contact with the transmission bar.

![Figure 3](image.png)

**Figure 3.** Test the uniformity of stress state of specimen. (a) The three-wave method; (b) End stress state method

3. **Study on rock dynamic characteristics under different loading conditions**

3.1. **Loading with different peak stress**

3.1.1. **Stress loading process analysis.** Dynamic uniaxial compression tests were carried out at the end of the incident bar under different peak stresses (100, 150, 200, 250, 300, 350, 400, 500, 600 MPa) respectively. Calculation results of stress wave signals are shown in Figure 4 below. As can be seen from the figure, as the stress amplitude of incident wave increases, on the one hand, the stress amplitude of reflected wave increases significantly, indicating that the strain rate of the specimen increases during the loading process. On the other hand, the amplitude of the transmitted wave moves forward with the peak time, and the duration decreases and increases, indicating that the higher the
peak strength of the specimen, the shorter the loading time. In addition, there are two typical modes in these reflected waves. Under the action of low peak stress, the reflected wave rises gradually at first; when the loading stress decreases gradually, the reflected wave decreases continuously, and the tail of the reflected wave appears negative value. On the contrary, under the action of the peak stress, the reflected wave is a spreading wave in its entire section. Comprehensive analysis, in a relatively small peak stress, the full load (i.e., the rise of incident wave) during the specimen has not been broken and at the moment of impact energy at a certain strain energy stored in the specimen, and then into the (i.e. the down part of the incident wave) during unloading, stored energy will be gradually released into the bar. This is what we call a springback phenomenon, and it causes a reverse compression wave. However, under the action of large peak stress, the specimen will be destroyed during the loading stage, and the stored energy will be released instantly in the form of kinetic energy, surface energy or other energy, so the compression wave will not appear. The results show that with the increase of the peak stress, the reflected wave tends to be flat, and the strain rate of the specimen is basically unchanged. However, as the peak stress increases, a protrusion higher than the front platform becomes more and more obvious in the back part of the reflected wave. Therefore, a constant strain rate during the whole loading process cannot be guaranteed under the action of this extremely high peak stress.

![Figure 4. Stress waveforms under different peak loads](image)

3.1.2. Stress strain analysis. According to the measurement circle, the stress-strain curves of granite specimen under different peak stresses are shown in Fig. 5. Under different peak loading stresses (100, 150, 200, 250, 300, 350, 400, 500, 600 MPa), the strain rates are 38.8, 59.6, 77.4, 92.5, 106.5, 117.7, 132.7, 146.0, 164.1 s⁻¹, respectively. The dynamic compressive strengths are 94.31, 109.88, 114.98, 118.35, 120.40, 122.97, 124.77, 128.39, 130.64 MPa. Under low impact stress (100 MPa), the stress-strain curve can be roughly divided into the elastic stage, the internal crack growth stage and the rebound stage. The damage of the rock specimen does not appear significant breakage. In the process of stress unloading, it is almost the same as the elastic stage, and the residual strain is small. When the impact stress gradually increases to the point that the specimen can be destroyed, the stress-strain curve at this point can be roughly divided into the elastic stage, the internal crack growth stage and the failure stage. In this stage, the specimen presents a state of integrity, rupture and commin, and the residual strain gradually increases. Granite is a typical brittle material under the action of dynamic compression, and the elastic modulus of the rock basically remains unchanged in the elastic stage. According to Figure 6 and Figure 7, with the increase of peak loading stress, the strain rate and dynamic compressive strength of granite gradually increase, showing an obvious rate correlation.
Figure 5. Stress-strain curves under different peak loading stresses

Figure 6. The relationship between different peak loading stress and strain rate and dynamic compressive strength

Figure 7. Relationship curve between strain rate and dynamic compressive strength

3.1.3. Crack propagation process analysis. According to the statistical information of cracks in the whole loading process (see Figure 8. and Figure 9.), we can see that in the dynamic compression loading test, the incident end of the specimen and the periphery of the specimen are the first to be damaged by force. With the continuous propagation of stress waves, the cracks continue to expand and penetrate, and the specimen volume keeps expanding. When the stress value exceeds the limit value that the specimen can withstand, the specimen is completely broken. In addition, the additional energy that can not be dissipated will promote the specimen to further crush. The compression process, the edges from specimen center degree of damage is relatively serious, according to the crack graph, tension crack first appeared in the process of specimen loading, with the increase of stress, tension crack gradually increase the stable range, shear crack appeared later than the tensile crack, and to be less than the tensile crack in number. From block size distribution, the specimen after stress load with impact load value increased, the specimen of the strain rate also gradually enhanced, the specimen had better integrity at a lower strain rate, just on the edge of broken, impact load increase, the block specimen after crushing also gradually reduced, block numbers also gradually increased, or even
shattered. Therefore, according to comprehensive analysis, the failure process of rock under impact load can be divided into elastic deformation stage (no crack appears), crack initiation and propagation stage, rapid crack propagation stage and slow crack propagation stage. The main fracture degree of the specimen presents the transformation of integrity, crack expansion, crushing and crushing.

![Figure 8. Timing process diagram of crack information during loading. (a) 100MPa; (b) 600MPa;](image)

![Figure 9. Statistics of crack and block information under different impact loads. (a) Statistics of tensile cracks (red disk) and shear cracks (pink disk); (b) Block diagram with powder removed](image)

4. Conclusion

In this paper, numerical simulation software is used to simulate the dynamic impact compression and crushing of brittle rocks to verify the feasibility of the 3D model in rock dynamics experimental research. Firstly, the PFC-FLAC coupling technology was used to solve the problem of 3D discrete element SHPB model establishment. The rock and bar meso-parameters were calibrated through the experimental parameters, so as to realize the correct application of dynamic load and the monitoring of crack growth during the whole process. Meanwhile, the dynamic uniaxial compression process was simulated for different peak stress loads. The summary is as follows:

(1) The three-dimensional SHPB model based on the PFC-FLAC coupling scheme is verified by the calculation results of one-dimensional propagation and stress uniformity of the specimen, which provides a new approach for realizing the evolution of microstructure and the change of macroscopic response.

(2) The strain rate effect is obvious under different peak loading stress. With the increase of loading stress, the compressive strength of the specimen increases gradually, the number of cracks increases, and the block becomes more crushed.

(3) Under impact load, the evolution of crack controls the failure process and final failure mode of joint specimen. Before reaching the peak stress, a few tensile cracks and shear cracks appeared in the
specimen, and after reaching the peak stress, the tensile cracks and shear cracks in the specimen increased rapidly. During the whole loading process, the cracks mainly formed in the post-peak stage, and the number of tensile cracks was far more than that of shear cracks, and the tensile cracks were dominant, indicating that the tensile splitting failure was the main failure of the specimen.

Acknowledgments
This work was supported by the Research on precision crushing technology and equipment for deepwater hard rock (2019-ZJKJ-22).

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