Experimental investigation on the strain energy evolution mechanism of granite specimens with a single flaw

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Abstract. Damage and fracture of rocks is a comprehensive result of strain energy dissipation and release. In order to study the energy evolution mechanism of hard brittle rock masses during failure process, uniaxial compression tests on the granite specimens with a single pre-existing flaw are carried out with digital image correlation method (DIC). The results indicate that: (1) The stress fluctuation before structural failure corresponds to the sudden increase of the dissipated energy, the essence is that rock masses occur obviously damage and cracking. (2) For medium flaw dip angles, the stress fluctuation occurs repeatedly in stages, whose strain energy is dissipated gradually; for large or small dip angles, the stress fluctuation is almost not appeared, and the energy dissipation is insignificant. (3) With the increase of flaw dip angles, the dissipated energy ratio at the peak stress first increases and then decreases showing an inverted U-shaped, resulting in a similar law of rock damage but a contrary law of strength; the corresponding elastic energy ratio is U-shaped of decreasing first and then increasing, causing the structural failure changes from dynamic to static and then to dynamic again. The results can provide theoretical references for the formation mechanism and prevention method of dynamic disasters of rock underground engineering.

1. Introduction
The deformation characteristics and fracture behaviour of surrounding rock has always been an important focus in the stability analysis and evaluation of rock underground engineering. Due to the unavoidable natural defects of engineering rock mass, the mechanical behaviour of deformation and failure of rock mass is obviously varied for the different occurrence environment, and it is difficult for the classical elastoplasticity to analyse effectively [1]. Therefore, Xie points out from the perspective of non-equilibrium thermodynamics that the deformation and failure process of rock always exchanges material and energy with the surroundings, and it is in essence a comprehensive driving result of energy dissipation and energy release [2]. In this way, an energy analysis framework for rock mass strength and structural failure is established, which provides a new idea for the research work in this field [3].

In recent years, many scholars, with the rock energy theory, have acquired fruitful achievements in the researches of static and dynamic damage and fracture mechanism of rocks in many fields, such as stability analysis of underground chambers [4, 5], catastrophe theory of karst tunnel [6, 7], rock burst [8,9] and so on. Although the existing researches with laboratory experiments or numerical simulations have different aims, they mostly focus on integrated rock specimens. However, the study...
on the energy mechanism of flawed rock mass has not been generally carried out, and there have been very limited reports. Wang et al. studied the energy characteristics of pre-existing non-persistent jointed sandstone and discussed the effect of crack dip angles [10, 11]. Niu et al. carried out a re-fracture test on flawed rock specimens collected on site and studied the energy dissipation laws of engineering fractured rock mass [12, 13]. In fact, for the flawed rock masses, especially hard brittle flawed, their pre-existing flaws have the capacity of inducing damage and cracking propagation, and they have large brittleness but small plastic deformation, so it is easy to observe the rock mass damage and fracture phenomenon corresponding to small energy change in tests. Therefore, in the study of rock damage and fracture mechanism, flawed rock masses have certain advantages over the sudden failure of intact hard rock. Although it is not difficult to fully explain in theoretical perspective that energy dissipation drives the rock to damage and energy release causes the abrupt structural failure, the direct and accurate observation of the damage and fracture behaviour corresponding to energy dissipation in tests has not been reported. Therefore, the researches, focusing on the internal energy driving mechanism of static and dynamic failure of rock masses, still needs to be further developed.

In this study, the typical hard brittle granite specimens with a single flaw are selected as the object of uniaxial compression tests, where the advantages of using pre-existing flaw to induce rock damage and crack were fully utilized. Combined with the DIC method and strain energy theory, the damage and fracture behaviour of rock mass corresponding to energy dissipation are accurately captured. Then, the internal mechanism of the failure characteristics is revealed from the perspective of energy dissipation. Furthermore, from the perspective of energy storage and release, the intrinsic causes of dynamic and static characteristics of structural failure are analysed. The results are helpful to reveal the formation mechanism of dynamic disaster of rock mass underground engineering, and provide ideas for its prevention and control technology.

2. Experimental methods

2.1. Specimens preparation

The granite used in the experiment is produced in Pingyi County, Shandong Province. The main components are feldspar, quartz, and mica, and the appearance is fleshy red. Its physical and mechanical parameters are shown in table 1.

| Parameters | Values |
|------------|--------|
| Uniaxial compressive strength (MPa) | 127.94 |
| Brazilian tensile strength (MPa) | 6.49 |
| Young’s Modulus (GPa) | 77.16 |
| Poisson’s ratio | 0.23 |
| Intact friction angle (°) | 48.90 |
| Intact material Cohesion (MPa) | 46.80 |

**Figure 1.** Specimen preparation procedure.

Before the test, the granite is processed into a rectangular thick plate with a length of 150mm, width of 75mm and thickness of 20mm, and a flaw with a length of 13mm and width of 1mm is manufactured at the center of the specimen by water jet cutting (figure 1a). Flaws have 7 dip angles: α=0°, 15°, 30°, 45°, 60°, 75° and 90°, which is the angles to the axial stress acting plane in uniaxial compression tests. Then the speckles are sprayed on the surface to form the black and white-staggered
and uniformly randomly distributed speckles (figure 1b), so that the small displacement of the specimen surface can be captured by a high-speed camera, to realize the application of DIC technology in rock deformation monitoring. Then the speckle quality is evaluated with self-developed codes, one result is demonstrated in figure 1c. For specific evaluation methods, see literature [14].

2.2. Test setup and procedure
The main test equipment includes an axial force loading device, a high-speed camera, two supplementary light sources and two computers, as shown in figure 1d. Axial force loading adopts 600kN electro-hydraulic servo rock uniaxial compression instrument with displacement control loading mode and 0.2mm/min load speed. At the same time, the high-speed camera is used to take pictures of the whole test process, with a frequency of 500 images per second. In the picture post-processing task, the open source software Ncorr [15] is adopted to calculate the global strain fields and displacement fields.

3. The energy dissipation mechanism of flawed granite specimens

3.1. The stress fluctuations phenomenon of the σ-ε curves
The σ-ε curves of the granite specimens are shown in figure 2. The rock specimens all have similar pore and flaw compaction stage at the beginning, but then the curves show different degrees of jumping fluctuations and stress drops. The stress fluctuation has a certain regularity with the changing of flaw dip angle. For the seven specimens, when the angles between pre-existing flaw and axial stresses (i.e. the maximum principal stress) is maximum or minimum, i.e. \( \alpha = 90^\circ \) or \( \alpha = 0^\circ \), the peak strength is the highest, the curve is relatively smooth and the stress fluctuation is almost not appeared. When the angles are medium (i.e. \( \alpha = 30^\circ, 45^\circ \) and \( 60^\circ \)), the peak strength is low, and the stress fluctuation starts early and lasts long with obvious stage characteristics, showing strong fluctuation phenomenon; when \( \alpha = 15^\circ \) and \( 75^\circ \), the stress fluctuate degree is between the above two types.

![Figure 2. The σ-ε curves for the specimens with varied \( \alpha \) and Figure 3. Relation between \( U^d \) and \( U^e \) during rock failure.](image)

Similar phenomena have been observed by some researchers in their compression tests of pre-existing flawed or natural flawed rock masses [10-13]. They found that, compared with the complete rock specimens, the flawed exhibit different degrees of stress fluctuations in the middle and late stages of the elastic deformation stage, and divided the σ-ε curve into single-peak curves and multi-peak curves. Stress fluctuation phenomenon is generally believed having relationship to crack initiation and propagation. However, the information obtained is limited only depends on σ-ε curves. The analysis of the deformation and cracking characteristics of the flawed rock mass from the energy-driven perspective will help to reveal the rock damage and failure mechanism hidden behind the classical rock strength theory [1].

3.2. Rock mass damage analysis from the energy dissipation perspective
Considering the deformation of a rock specimen under the action of external force, assuming that no heat exchange occurs between the test process and the surroundings, suppose it as a closed system. The total energy input by the external force to the unit cell of rock specimens is \( U \), according to the first law of thermodynamics [1]:

\[
\text{Net energy input} = \begin{cases} 
\text{Increase in stored energy,} & \text{if } \sigma > 0 \\
\text{Decrease in stored energy,} & \text{if } \sigma < 0 
\end{cases}
\]
where, $U^e$ is the releasable elastic strain energy stored in the rock; $U^d$ is the dissipated energy.

The relationship between $U^e$ and $U^d$ is shown in figure 3. The area enclosed by the $\sigma$-$\epsilon$ curve and the unloading elastic modulus $E_i$ is $U^d$, which represents the energy consumed by rock damages and plastic deformation. For brittle rocks, energy dissipation is mainly used for the surface energy that needed for crack initiation and propagation. The yellow shaded area represents $U^e$, which can be released after unloading. Before the structural failure, $U^e$ is stored in the rock. When arriving the energy storage limit, the rapid release of a large amount of $U^e$ is the internal cause of the abrupt structural failure [1]. Under uniaxial compression, only the axial stress $\sigma_i$ participates in the work. The strain energy can be expressed as [1]:

$$U = U^d + U^e$$  \hspace{1cm} (1)

$$U^e = \int_0^{\epsilon_0} \sigma_i d\epsilon_i$$  \hspace{1cm} (2)

$$U^e = \frac{\sigma_i^2}{2E_i} \approx \frac{\sigma_i^2}{2E_0}$$  \hspace{1cm} (3)

$$U^d = \int_0^{\epsilon_0} \sigma_i d\epsilon_i - \frac{\sigma_i^2}{2E_0}$$  \hspace{1cm} (4)

where, $\epsilon_i$ is the axial strain; to be convenient for calculation in engineering, $E_i$ can be approximately replaced by the elastic modulus $E_0$.

Further excavation of test data according to equations (2) ~ (4), the strain energy ($U$, $U^e$, and $U^d$) evolution characteristics during deformation and failure are obtained. Further processing, the real-time evolution curves of the ratio of elastic energy to total energy $U^e/U$ and the ratio of dissipated energy to total energy $U^d/U$ are also acquired. Due to that damages and crack propagation accompany by energy dissipation in brittle rock, we pay more attention to the evolution characteristics of $U^e$ here.

Figure 4a shows the strain energy evolution curve of the 75° specimen during the uniaxial compression tests, and figure 4b illustrates the corresponding strain energy ratio curves. The representativeness of this specimen is that its $\sigma$-$\epsilon$ curve and strain energy curve are smooth on the whole, with only a sudden change before the peak stress, which is convenient to analyse the mechanical behaviour corresponding to the sudden change of stress. In the initial stage of compression, $U^d/U$ is relatively large, but the overall $U^d$ is very small. The tiny primary voids in the rock mass are closed, and the rock is only very slightly damaged, which consumes very little energy. As the rock mass gradually compacted, $U^d/U$ drops rapidly, $U^e/U$ increases correspondingly and the initial damage stage is completed. The total energy is mainly converted into $U^e$ and stored in the rock mass. Energy dissipation is extremely small, and $U^d$ shows a relatively long approximate-horizontal platform, the rock damage tends to be stable. Then, $U^d$ increases sharply (the AC segment in figure 4a), the $\sigma$-$\epsilon$ curve and the $U^e$ curve fluctuated, and the $U^d$ curve in the CD segment after the fluctuating entered an approximate-horizontal platform again. Subsequently, the $\sigma$-$\epsilon$ curve and $U^e$ curve reached the peak value, the rock specimens reached their energy storage limit, a large amount of elastic energy released rapidly in a very short time, and the structural failure occurred. It should be pointed out here that $U^d$ also increases in the approximate-horizontal platform segment, but the increase is minimal compared to the before and the after segment, so the platform showed approximate horizontal characteristics.

Specifically, $U^d$ suddenly increased sharply in the AC segment, and the growth before and after the AC segment is very insignificant where the curve shows an approximate-horizontal platform. This "step-like" mutation phenomenon of $U^d$ has also been reported in other literatures [10, 11, 16]. Using experimental methods to directly observe the rock damage and cracking behaviour corresponding to dissipated energy sudden change segment is an intuitionistic method to reveal the mechanical essence behind this phenomenon. The application of DIC technology makes it possible. In the experiment, the DIC technology was used to obtain the principal strain cloud diagrams corresponding to the sudden change segment start point A, a point B and the end point C, as shown in figure 5a~c, and the corresponding horizontal displacement cloud diagrams is shown in figure 5d~f. Noted that, since there is almost no change in other areas, figure 5 only illustrates the area of interest around the flaw. Point A
is the starting point of AC and also the end point of the former approximate-horizontal platform. Only high strain appears at the end of the pre-existing flaw, with almost no obvious damage to the entire specimen (figure 5a). The specimen is still relatively intact, and the horizontal displacement is also relatively uniform (figure 5d). 94% of the energy input by the testing machine is converted into $U^e$ and stored (figure 4b). After point A, the dissipated energy curve gradually rises, and the rock mass appears obvious energy dissipation behaviour. Point B is a point in the process and its principal strain is shown in figure 5b. Here, the two ends of the pre-existing flaw forms non-persistent small-scale strain localization zones toward the two ends of the specimen. The horizontal displacement field has had a tendency to partitioning, and some micro-cracks appeared around the flaw. The increased $U^d$ is mainly used for the formation and development of micro-cracks. Then, $U^d$ continues to increase and reaches the point C. It can be observed from figure 5c that the non-persistent strain localization zones have been connected to each other, forming some macroscopic cracks extending to the end of the specimen, and splitting the specimen into three incomplete independent pieces. The entire AC segment reflects that the incensement of $U^d$ has induced damage and crack propagation to a certain extent, which promotes the damage and degradation of rock masses. But the crack has not penetrated the entire rock specimen, and the splited parts still have some connection, so the structure failure has not been caused now. $U^d$ in the subsequent CD segment is almost stable, and the energy is mainly conversed to $U^e$ (figure 4a), and the rock specimen still has a certain resistance.

Figure 4. Strain energy evolution characteristics of the specimen with $\alpha=75^\circ$. (a) Strain energy evolution curve; (b) Strain energy ratio evolution curve.

Figure 5. (a)−(c) The principle strain field of point A, B and C; (d)−(f) The x-displacement field of point A, B and C.

From the above analysis, it can be concluded that, for hard brittle rock masses, stress fluctuating accompanies an abrupt increase in dissipated energy, which drives the development of micro-cracks and induces the damage and degradation of material properties. However, as shown in figure 2, the stress fluctuations for the specimens with varied $\alpha$ are significantly different, indicating that their energy dissipation characteristics are unlike, which in turn causes different damage and fracture characteristics. Specifically, for those with medium flaw angles (i.e. $\alpha=30^\circ$, $45^\circ$ and $60^\circ$), the stress fluctuation occurs continuously in stages, so the strain energy is gradually dissipated before structural failure, and the rock mass is cumulatively damaged, showing progressive failure characteristics. For
the specimens with $\alpha=90^\circ$ or $\alpha=0^\circ$, the stress fluctuation is almost not appeared, and the energy dissipation is very insignificant, causing a sudden failure.

4. The mechanism of structural failure driven by strain energy

Figure 6 exhibits the peak strength of the specimens with varied $\alpha$. It generally shows asymmetrical distribution characteristics that first decreases and then increases, which are in favourable agreement with the results obtained by Wang and Chen through indoor tests and numerical simulations [11, 17]. This illustrates that flaw dip angles have a significant effect on rock strength. Xie pointed out that the dissipated energy is used to form rock mass damage, resulting in the loss of strength, and the amount of energy dissipation reflects the attenuation degree of original strength [1]. In order to reveal the physical essence between rock strength and energy dissipation, and to explore the internal connection between energy release and structural failure, the strain energy corresponding to the peak point of the stress is calculated and normalized to obtain the elastic energy ratio $U^e/U$ and the dissipated energy $U^d/U$, as shown in figure 7.

![Figure 6. Peak strength of the specimens with varied flaw tip angles.](image)

With the increase of $\alpha$, $U^e/U$ has a downward trend from $0^\circ$ to $45^\circ$, and an upward trend from $45^\circ$ to $90^\circ$. The overall performance first decreases and then increases as a U-shape, and correspondingly $U^d/U$ shows inverted U-shaped change trend of first increases then decreases. During the loading process, energy dissipation drives the rock to produce irreversible strain change [18]. For hard brittle granite, the plastic deformation is very small, and the dissipated energy mainly drives rock cracking. The damage and cracking before the peak stress is an important reason for strength decrease. Therefore, the strength of the rock specimens (figure 6) and the $U^d$ (figure 7) show an opposite trend.

The elastic energy at the peak is the energy storage limit of the rock. Here $U^e/U$ represents the energy storage capacity of the rock specimens. The larger the value, the stronger the elastic energy storage capacity before structural failure. Elastic energy, as a releasable energy reserve, is the energy source for the structural failure. When it accumulates to a certain amount of the surface energy required for the structural failure, elastic energy is released and the structural failure occurs. When the two are equal, static failure occurs and rocks are broken along the main crack surface in two or three blocks; when the released elastic energy is greater than the surface energy required for failure, rocks undergo dynamic destruction, and the excess energy causes the rock blocks to be thrown out in the form of kinetic energy, resulting in rockburst [1]. In figure 7, when the angle between the flaw and the maximum principal stress is large or small ($\alpha=0^\circ$ and $90^\circ$), the maximum $U^e/U$ is 90.97% and 90.56%, respectively, and the corresponding $U^d/U$ is only 9.03% and 9.44 %. It demonstrates that only a very small part of the total energy before the structural failure is consumed by rock damage and crack propagation. The damage before peak stress is slight, and most of the energy converted into elastic energy and stored, which becomes a huge driving force for the structural failure. Taking $\alpha=0^\circ$ as an example, figure 8 shows the rapid capture of the structural failure process. The concentrated release of a large amount of elastic energy stored before peak stress caused strong failure. The specimen was severely destroyed and the rock fragments and rock dust spurted to the surroundings, showing obvious characteristics of rockburst. When the angle between the pre-existing flaw and the maximum principal stress tends to be medium (for example $\alpha=45^\circ$), $U^e/U$ is small, while $U^d/U$ increases, reaching the
minimum value of 52.5\% and the maximum value of 47.5\%, respectively. Before structural failure, almost half of the total energy is gradually dissipated due to progressive damage and cracking. The specimen is more seriously damaged and has less energy storage. Less elastic energy makes the structural failure mildly. A small amount of surface rock flakes was spalled, as shown in figure 9.

![Figure 8](image1.png)  ![Figure 9](image2.png)  ![Figure 10](image3.png)

**Figure 8.** Structural failure of the specimen with $\alpha=0^\circ$. (a) the failure time; (b) after failure.

**Figure 9.** Structural failure of the specimen with $\alpha=45^\circ$. (a) the failure time; (b) after failure.

**Figure 10.** The relationship between the failure intensity index and flaw tip angles.

In order to reflect the dynamic performance of rock failure, Lin et al. defined $U^*/U^d$ as the failure intensity index ($F_{d}$) at the moment of peak stress, and divided the dynamic failure level accordingly [18]: (1) when $F_{d} < 1$, the progressive and mild rock failure takes place; when $1 < F_{d} < 5$, the weak dynamic failure occurs; and (3) when $F_{d} > 5$, it is supposed as the strong dynamic failure. Using the theory, figure 10 calculated the $F_{d}$ of each specimen in this experiment. With the increase of $\alpha$, the $F_{d}$ is also U-shaped, where $\alpha=0^\circ$ and $\alpha=90^\circ$ are obviously larger, 10.08 and 9.60, respectively, indicating that the dynamic failure of the two specimens is stronger. $\alpha=45^\circ$ is the smallest, only 1.1, close to static failure. It is more consistent with the phenomena recorded in figures 8 and 9.

5. Conclusions

This paper reported a uniaxial compression test of flawed granite specimens combined with the DIC observation technology. Through the accurate capture of the failure process, the energy driving mechanism of damage and cracking of hard brittle rock mass are studied. The following conclusions are drawn:

(1) The DIC technology can accurately capture the mechanical behaviour of the rock mass corresponding to the energy dissipation. The experimental phenomenon intuitively reflects that the increase of dissipated energy during the failure process of hard brittle rock mass is the internal reason that drives the development of micro-cracks, induces the damage and leads to the degradation of material properties. It provided a strong experimental support for the energy dissipation theory.

(2) The stress fluctuation of the hard brittle flawed rock mass before peak stress accompanies an abrupt increase in dissipated energy. The essence is that rocks occur obviously damage and cracks formed or propagated. For the rock masses with medium flaw dip angles, the stress fluctuation occurs repeatedly in stages, and the strain energy is gradually dissipated before the structural failure; but for those with a large or small dip angle, the stress fluctuation is almost not appeared, and the energy dissipation is very insignificant.

(3) With the increase of flaw dip angles, the dissipated energy ratio $U^*/U$ at the peak stress first increases and then decreases showing an inverted U-shape; resulting a similar law of damage but a contrary law of strength; the corresponding elastic energy ratio $U^*/U$ shows a U-shaped trend of decreasing first and then increasing, causing the structural failure changes from dynamic to static and then to dynamic again.

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