中国矿业大学
China University of Mining and Technology

煤样三轴加卸载试验研究及临界冲击应力的确定

Experimental study on the characteristics of coal samples under three-dimensional loading-unloading condition and the determination of critical burst stress

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汇报提纲
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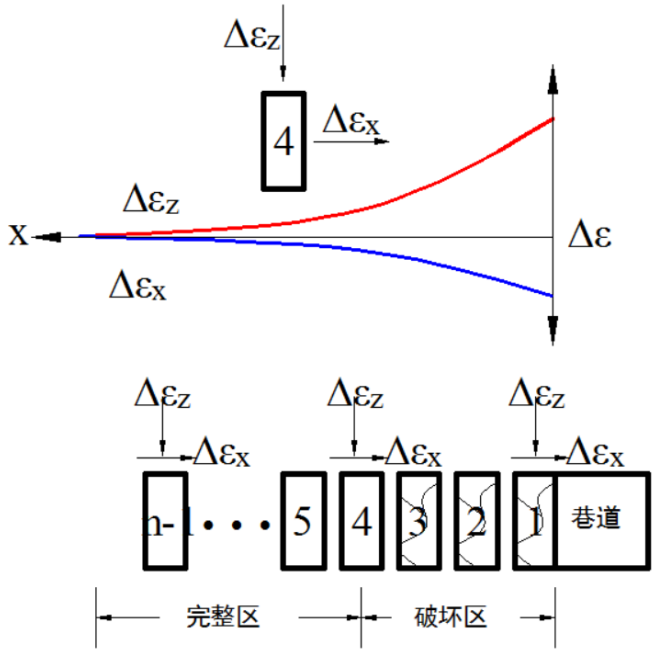
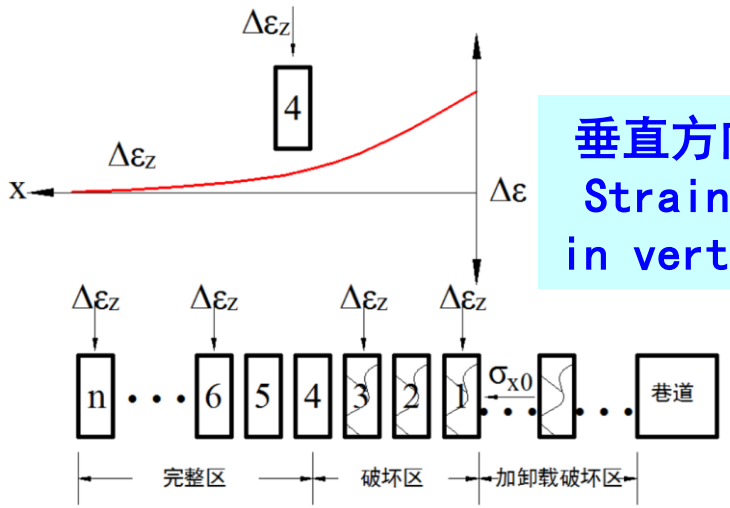
1. 巷道煤壁受力及加卸载试验系统
   Stress state of coal wall and load-unload test system
2. 加卸载三轴应力转换特征
   Characteristics of triaxial stress transformation under load-unload test
3. 试样加卸载影响因素分析
   Influencing factors for load-unload test of specimens

1.1 帮部煤体受力状态
Stress state of coal sidewall

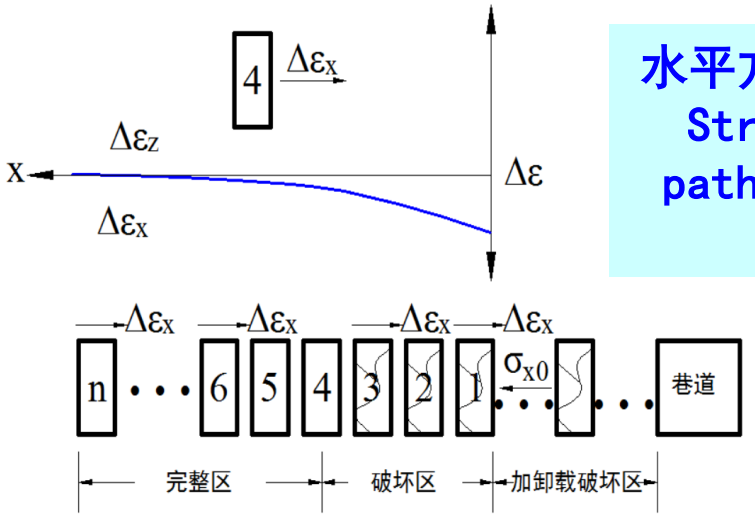
帮部煤体受力状态 Stress state of coal sidewall

切向加载 Tangential loading
径向卸载 Radial unloading
轴向应变不变 Axial strain unchanged





垂直方向应变加载路径
Strain loading path in vertical direction



水平方向应变卸载路径
Strain unloading path in horizontal direction

1.1 帮部煤体受力状态
Stress state of coal sidewall

卸加比定义 Unloading-loading ratio

应变卸加比 Unloading-loading ratio of strain:

水平应变速率与垂直应变速率之比

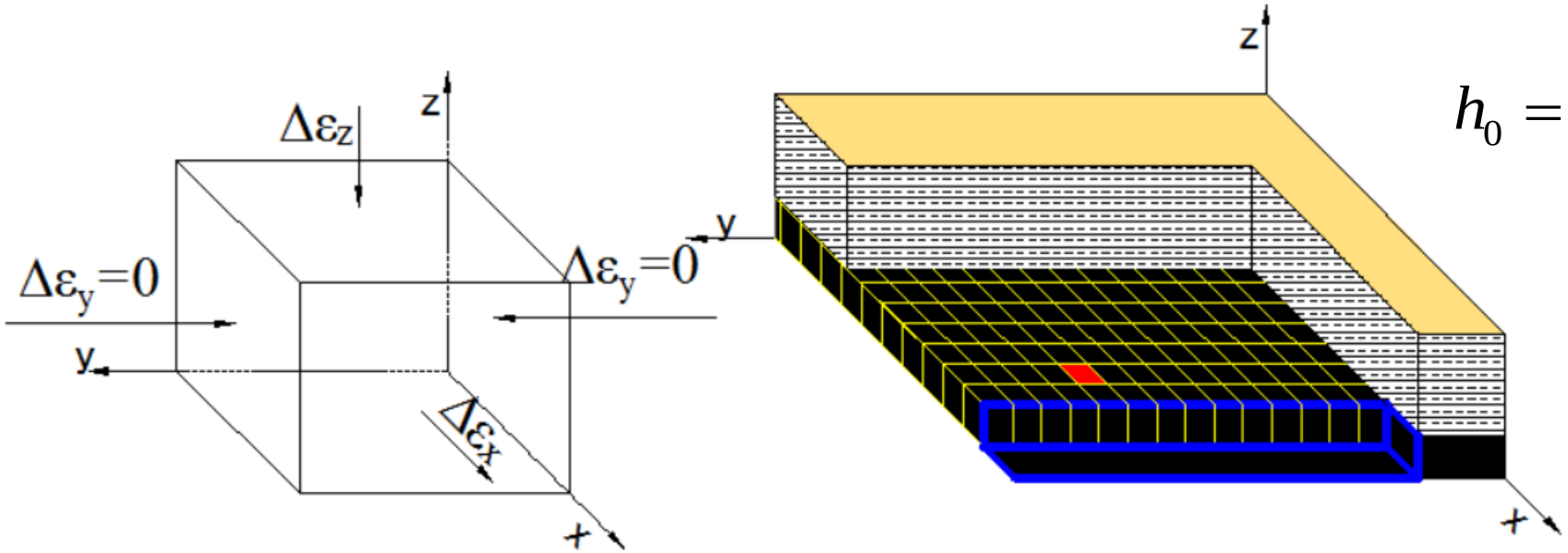
Ratio of horizontal strain rate to vertical strain rate

$$h' = \frac{\Delta\varepsilon_x}{\Delta\varepsilon_z}$$

应力卸加比 Unloading-loading ratio of stress:

水平应力变化速率与垂直应力变化速率之比

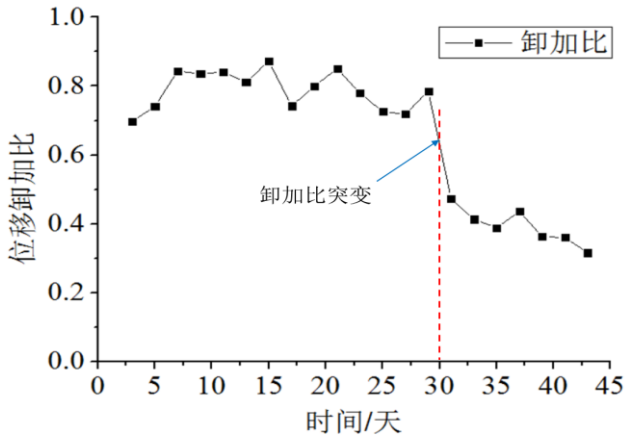
Ratio of horizontal stress change rate to vertical stress change rate



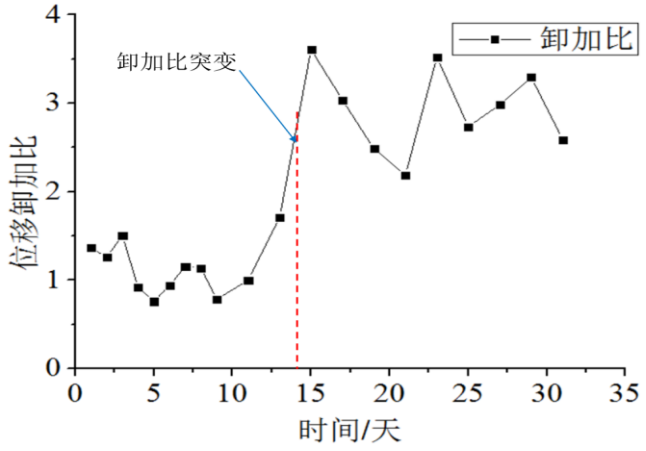
$$h_0 = \frac{\Delta\sigma_x}{\Delta\sigma_z} = \frac{(1-\mu)\cdot h'-\mu}{1-\mu-\mu\cdot h'}$$

1.1 帮部煤体受力状态
Stress state of coal sidewall

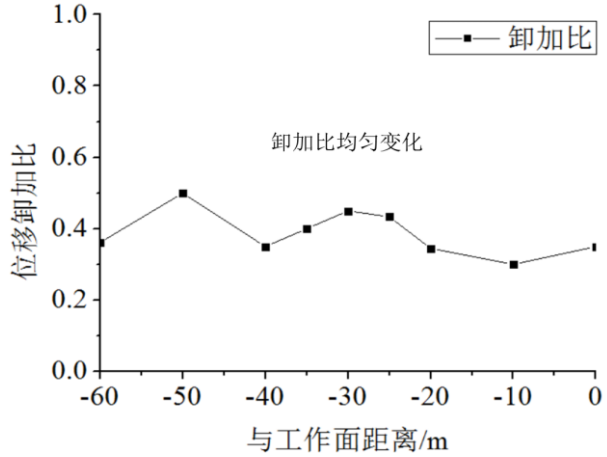
现场实测 Field measurement



A. 平煤十一矿掘进
A. Tunnelling in Pingmei No. 11 coalmine



B. 某矿3104面轨道巷掘进
B. Tunnelling in track roadway of LW3104



C、平煤十一矿回采
C. Mining in Pingmei No. 11 coalmine

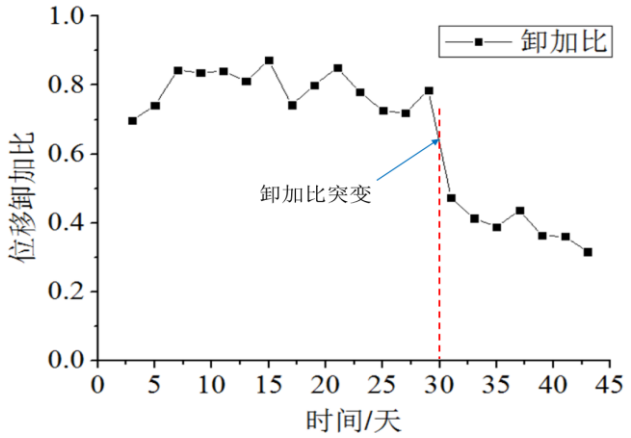
A—在巷道掘进30天时，应变卸加比产生突降，从0.8降为0.4；
On the 30th day of roadway excavation, the unloading-loading ratio of strain dropped sharply from 0.8 to 0.4.

B—在巷道掘进15天时，应变卸加比由1突增至3；
On the 15th day of roadway excavation, the unloading-loading ratio of strain increased suddenly from 1 to 3.

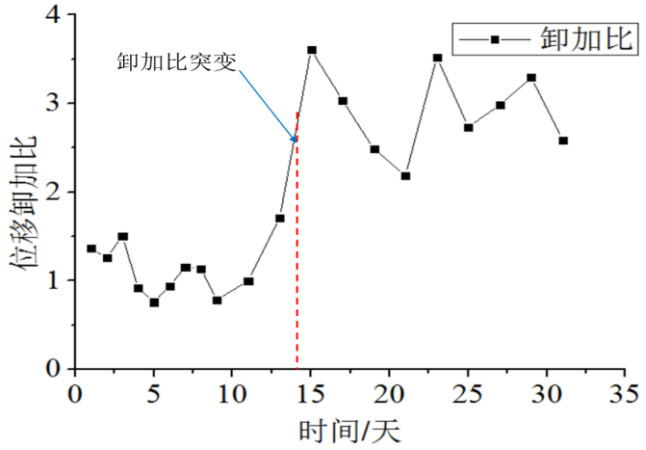
C—回采期间，应变卸加比始终保持在0.4上下浮动。
During the mining period, the unloading-loading ratio of strain always fluctuated around 0.4.

1.1 帮部煤体受力状态
Stress state of coal sidewall

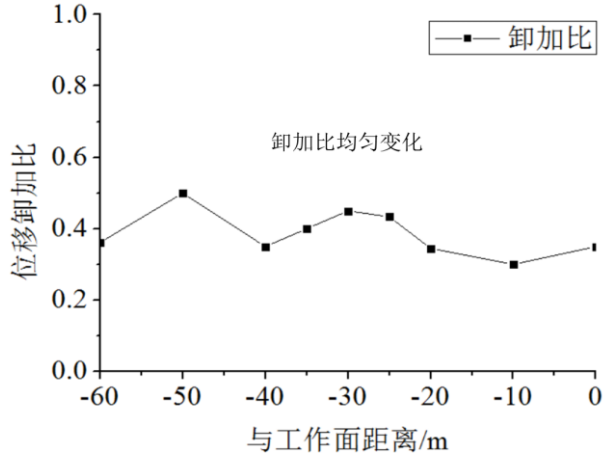
现场实测 Field measurement



A.平煤十一矿掘进
Tunnelling in Pingmei No.11 coalmine



B. 某矿3104面轨道巷掘进
Tunnelling in track roadway of LW3104



C、平煤十一矿回采
Mining in Pingmei No.11 coalmine

A

$$h' = \frac{\Delta\varepsilon_x}{\Delta\varepsilon_z} = 0.8 \rightarrow 0.4 \qquad h_0 = \frac{\Delta\sigma_x}{\Delta\sigma_z} = \rightarrow 0 \quad \Delta\sigma x=0$$

B

$$h' = \frac{\Delta\varepsilon_x}{\Delta\varepsilon_z} = 1.0 \rightarrow 3.0 \qquad h_0 = \frac{\Delta\sigma_x}{\Delta\sigma_z} = \rightarrow \infty \quad \Delta\sigma z=0$$

C

$$h' = \frac{\Delta\varepsilon_x}{\Delta\varepsilon_z} \approx 0.4 \qquad h_0 = \frac{\Delta\sigma_x}{\Delta\sigma_z} \approx 0 \quad \Delta\sigma x=0$$

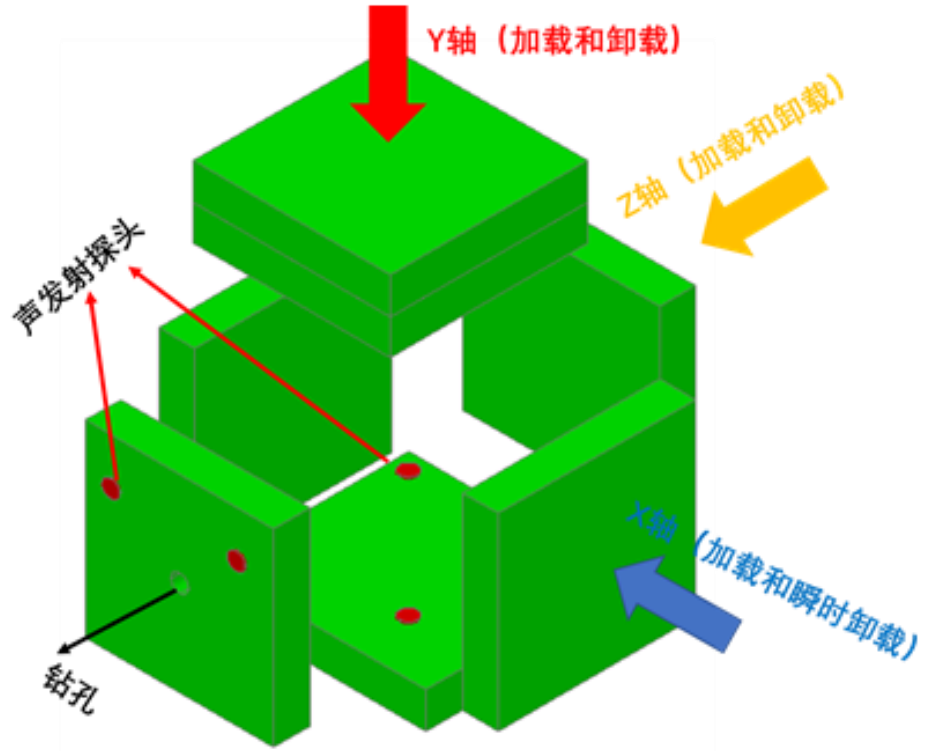
加卸载+加载
Loading-unloading + Loading

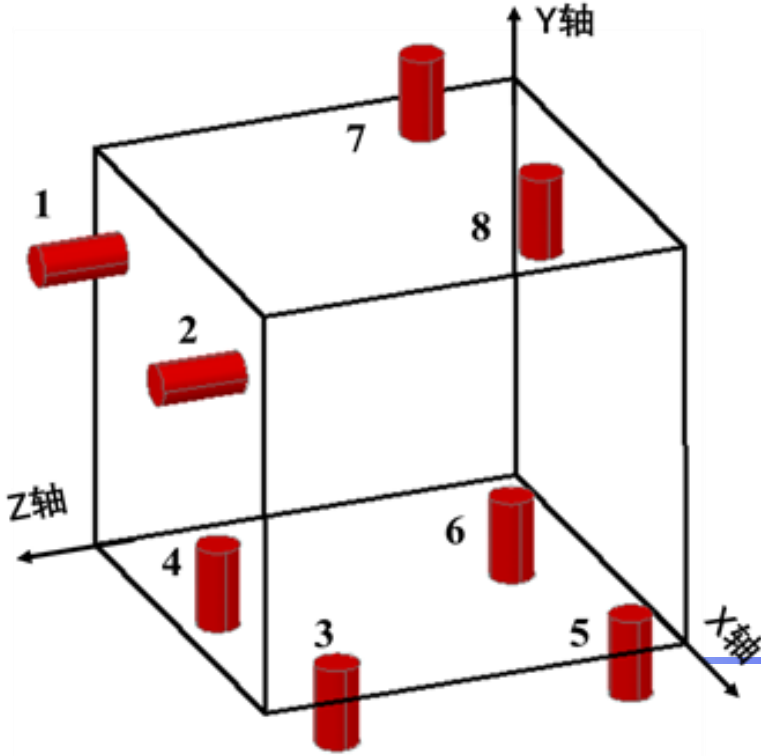
加卸载+卸载
Loading-unloading + Unloading

仅加载 Only loading

1.2 真三轴加卸载试验系统
True triaxial load-unload test system

- **模拟加卸载路径下试样应力演化**
  Simulating the stress evolution of specimens under stress path with load-unload-fix
- **揭示加卸应力路径试样破坏过程**
  Revealing failure process of specimens under stress path
- **揭示冲击破坏临界条件 Revealing critical condition for coal bursts**

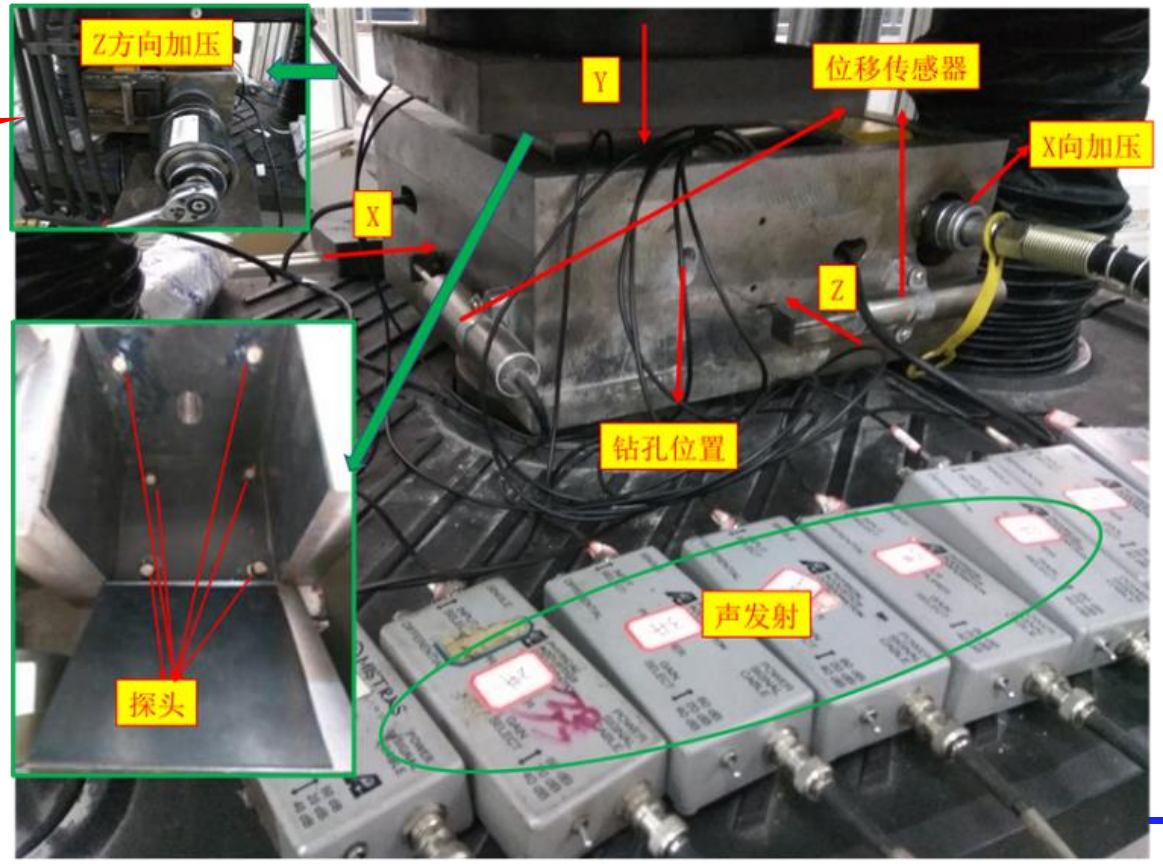




1.2 真三轴加卸载试验系统
True triaxial load-unload test system

- **X、Y、Z三向加载至不同初始应力，按照指定加卸载速率试验**

Specimens are loaded to different initial stresses in three directions and are tested at specified loading and unloading rates.



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2.1 “加-卸”应力路径下煤样破裂特征

Fracture characteristics of specimens under stress path with load-unload-fix

试验冲击定义 Coal burst in test：

- **人耳听到试样破裂的巨大声响；**

Loud noise of specimen rupture can be heard;

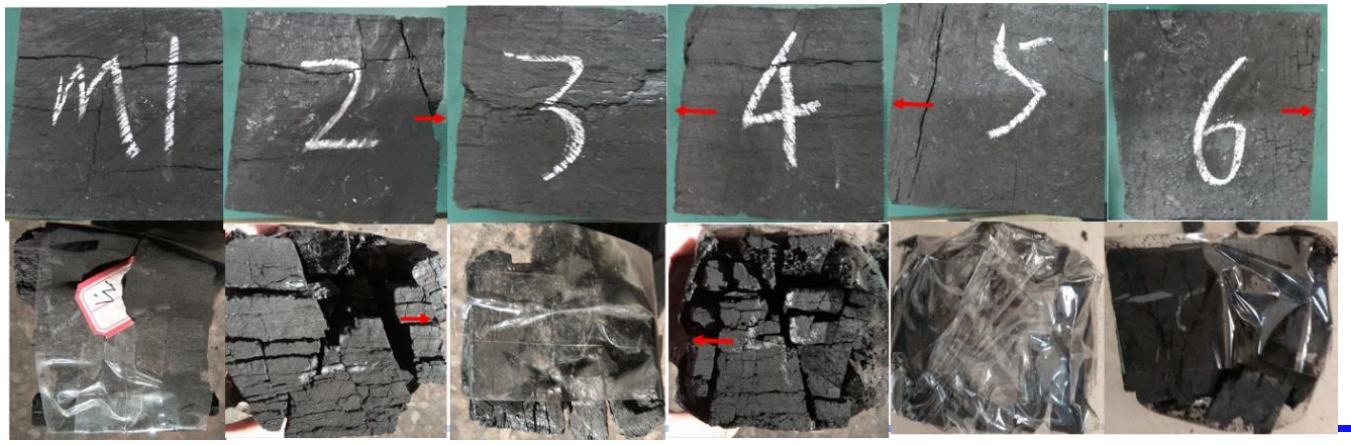
- **声发射能量:>1.0E+07μV·s;**

AE Energy:>1.0E+07μV·s；

- **应力应变曲线加载侧应力突降。**

Stress reduces suddenly at loading side in the stress-strain curve.

未冲击：层裂式 Non-burst：spallation



冲击：爆裂式 Coal burst：explosion

加卸载三轴应力转换特征
Characteristics of triaxial stress transformation under load-unload test

2.2 不同三向应力水平的“加-卸”应力路径曲线特征 2.2 Characteristics of stress path curves with load-unload-fix at different three-dimensional stress levels

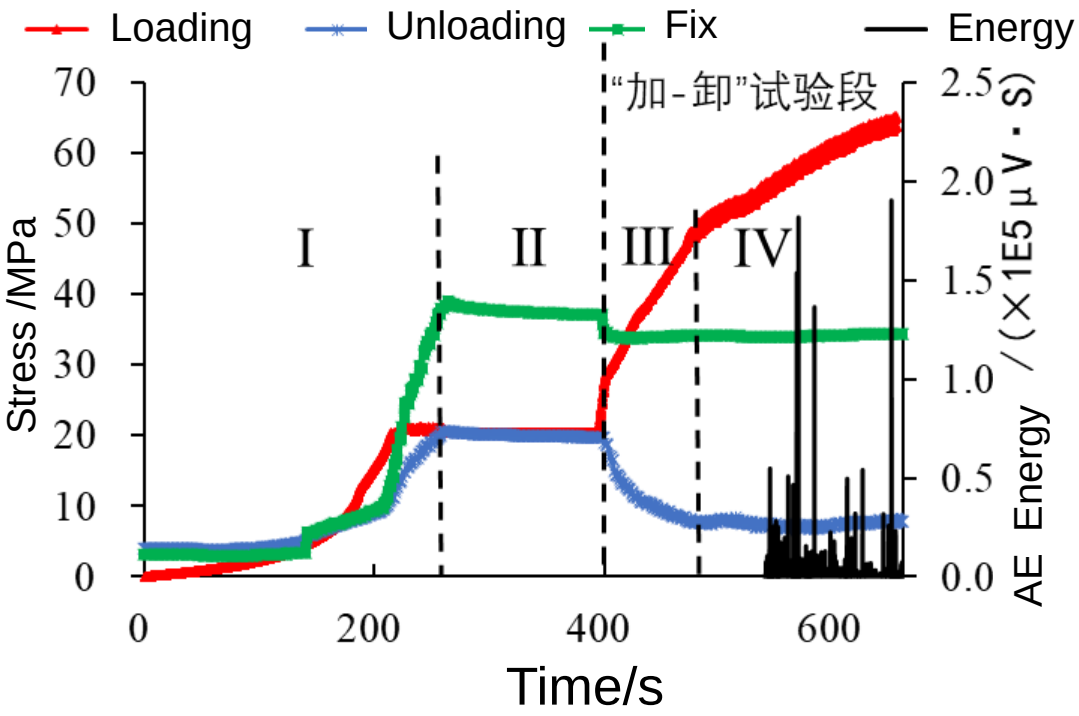
- **I—三向应力加载阶段：煤样受压裂隙闭合产生少量声发射事件；**

I—Three-dimensional loading stage: A few AE events occured due to fracture closure of compressed specimens;

- **II——应力保压阶段：三向应力进行微小的应力调整，基本不产生声发射现象**

II—Pressure-holding stage: Because tri-directional stress was adjusted slightly, there was almost no AE events;

- **Ⅲ——“加-卸”第一阶段：卸载侧应力降低、加载侧应力增加。无声发射，说明未出现大面积裂隙，处于弹性阶段。**
- **Ⅲ—1st stage of load-unload test: Stress at unloading side decreased while stress at loading side increased. The absence of AE events indicates there is no large area of cracks. Elastic stage**

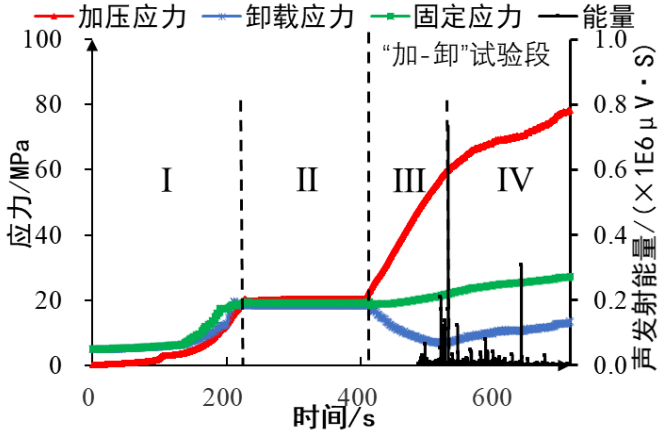


高固定侧应力 High stress at fixed side

加卸载三轴应力转换特征

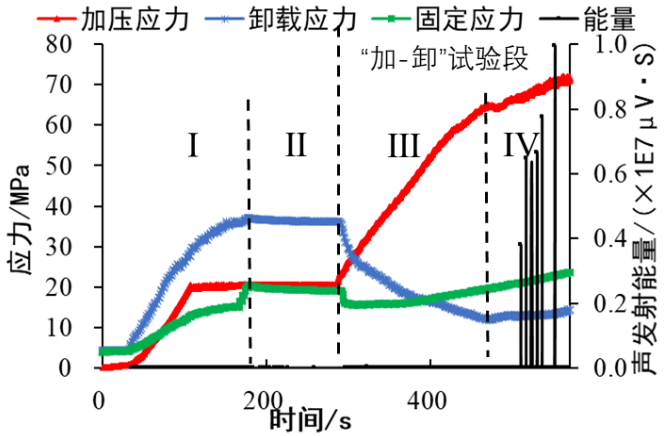
Characteristics of triaxial stress transformation under load-unload test

2.2 不同三向应力水平的“加-卸”应力路径曲线特征 2.2 Characteristics of stress path curves with load-unload-fix at different three-dimensional stress levels



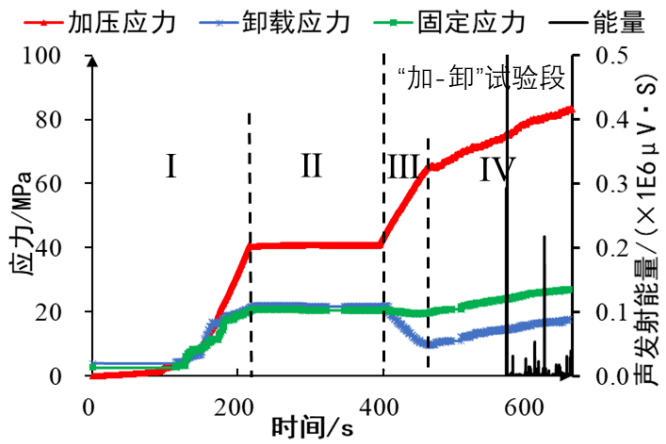
三向等压

Tri-directional isobaric



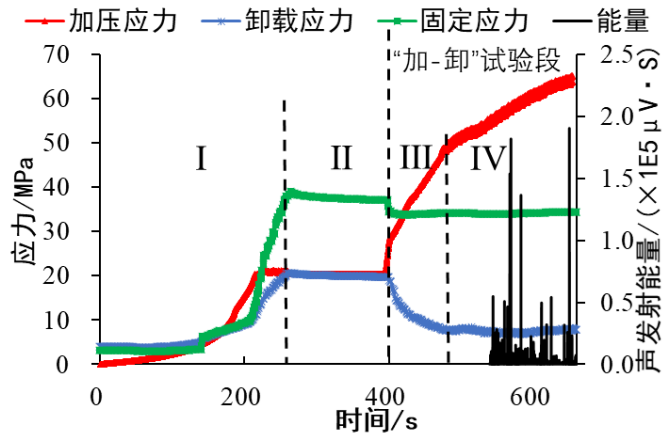
高卸载侧应力

High stress at unloading side



高加载侧应力

High stress at loading side



高固定侧应力 High stress at fixed side

- Ⅳ——“加-卸”第二阶段：卸载侧应力降低到一定值时，试样内部裂隙不断生成，扩容膨胀，声发射出现，试样进入塑性状态；
- Ⅳ—2nd stage of load-unload test: When stress on unloading side decreased to a certain value, cracks inside the specimen were generated continuously and the volume expanded, accompanied by AE events. Plastic stage

加卸载三轴应力转换特征

Characteristics of triaxial stress transformation under load-unload test

- **2.3 “加-卸”应力路径下煤样波速演化特征**
- **2.3 Evolution characteristics of specimen wave velocity under stress path with load-unload-fix**

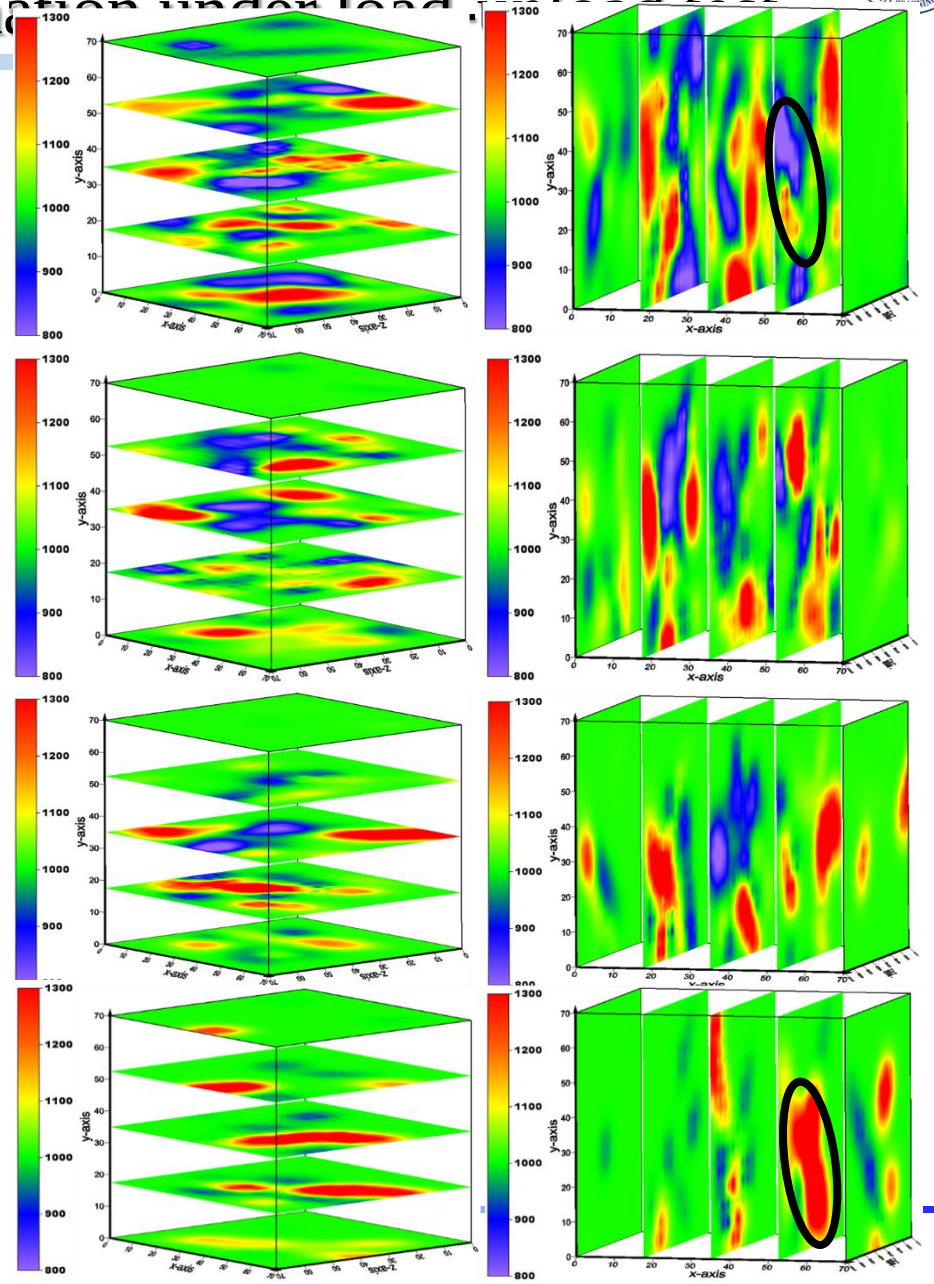
- **试样加载初期内部存在随机裂隙，高低波速区交替出现。**
- **At initial stage of loading, there were random cracks in specimens, and high and low wave velocity regions alternately occurred.**

Ⅰ阶段
Stage Ⅰ

Ⅲ阶段
Stage Ⅲ

Ⅳ阶段
Stage Ⅳ

高速卸载阶段
High-speed unloading stage



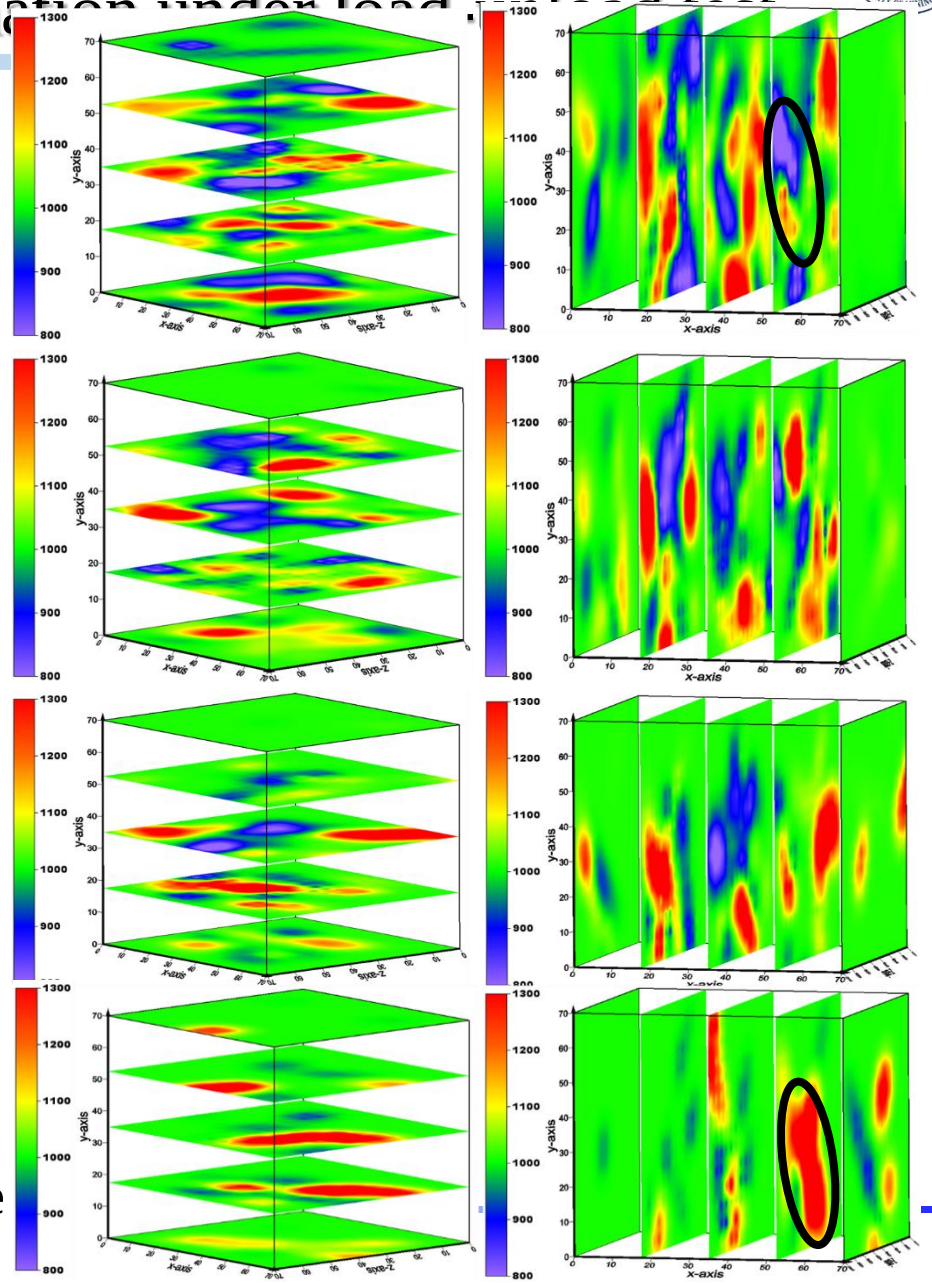
加卸载三轴应力转换特征

Characteristics of triaxial stress transformation under load-unload test

2.3 “加-卸”应力路径下煤样波速演化特征

2.3 Evolution characteristics of specimen wave velocity under stress path with load-unload-fix

- 随着实验的进行波速逐渐增加，低波速区逐渐消失，形成大面积高波速区。
- With the increase of wave velocity, the low wave velocity zone gradually disappeared, forming a large area of high wave velocity zone.
- 由低波速区向高波速区变化的区域，是主要的承载区域，为冲击矿压发生的潜在区域。
- The area changing from low wave velocity region to high wave velocity region is the main bearing area and the potential area of coal bursts.

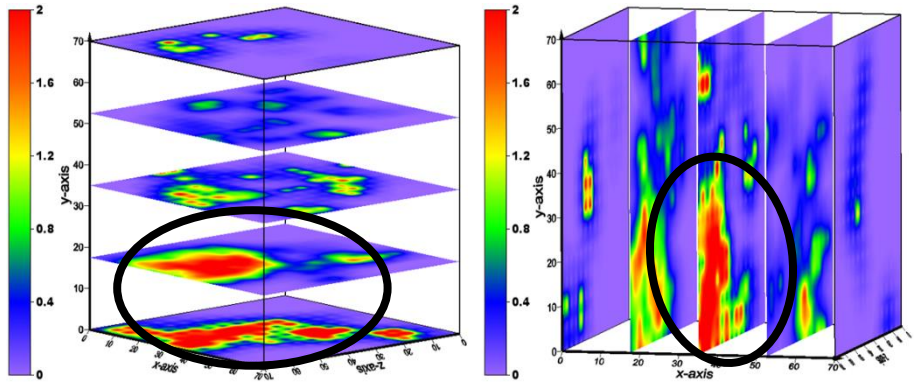


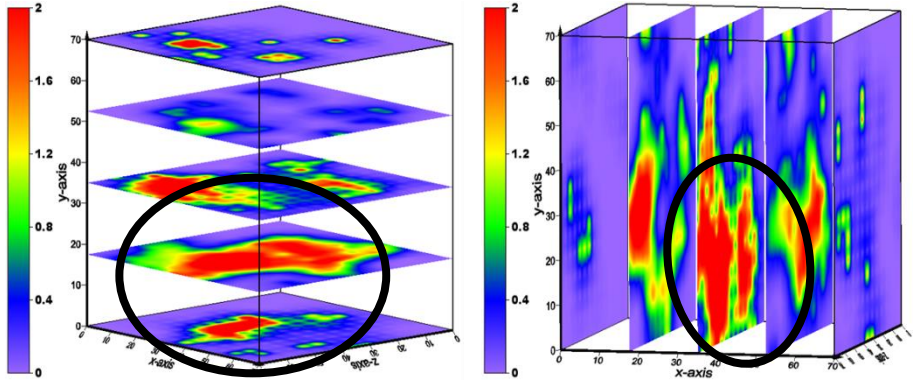
加卸载三轴应力转换特征
Characteristics of triaxial stress transformation under load-unload test

2.4 “加-卸”应力路径下煤样能量演化特征
Energy evolution characteristics of specimens under stress path with load-unload-fix

- 仅局部区域为高能量区，且各阶段变化较小，说明试样具有局部承载、破裂、释放能量特征。
- Only local region belongs to high energy region and the variation of each stage is small, which indicates specimen has the characteristics of local loading, fracture and energy release.

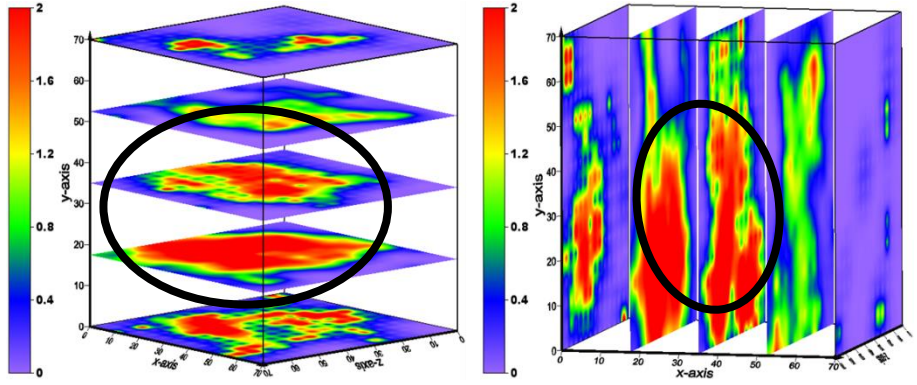
Ⅰ阶段
Stage Ⅰ

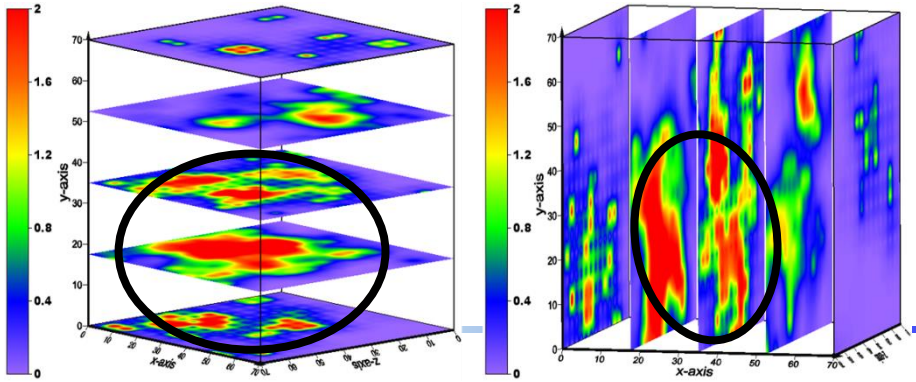




Ⅲ阶段
Stage Ⅲ

Ⅳ阶段
Stage Ⅳ





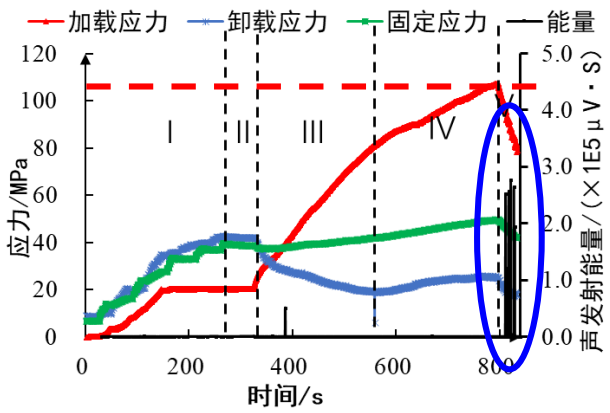
高速卸载阶段（冲击）
High-speed unloading stage (coal burst)

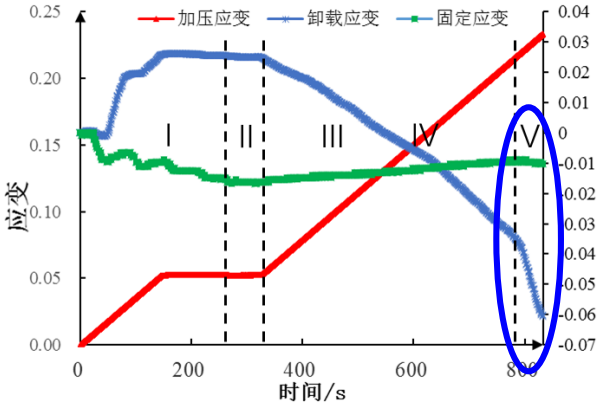
加卸载三轴应力转换特征

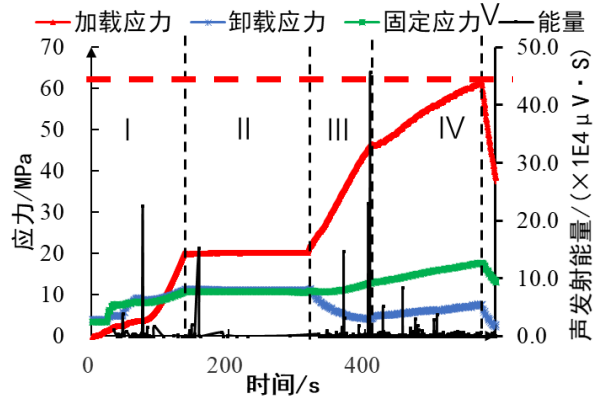
Characteristics of triaxial stress transformation under load-unload test

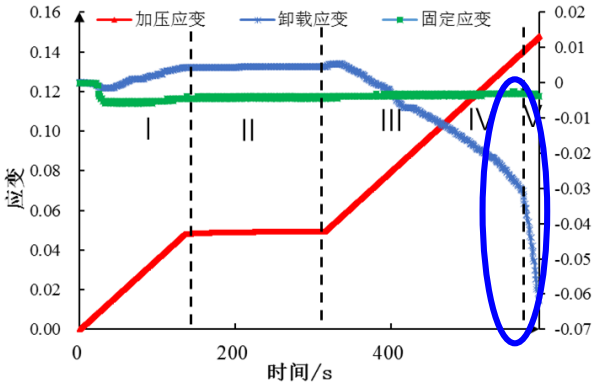
2.5 加-卸”应力路径下煤样冲击临界值

Coalburst critical value of specimens under stress path with load-unload-fix









冲击需要满足两个条件

Two conditions of coal bursts

- **卸载速率条件 Unloading rate：**

<1.128mm/min，未冲击 non-butst

>2.77mm/min ，冲击 burst

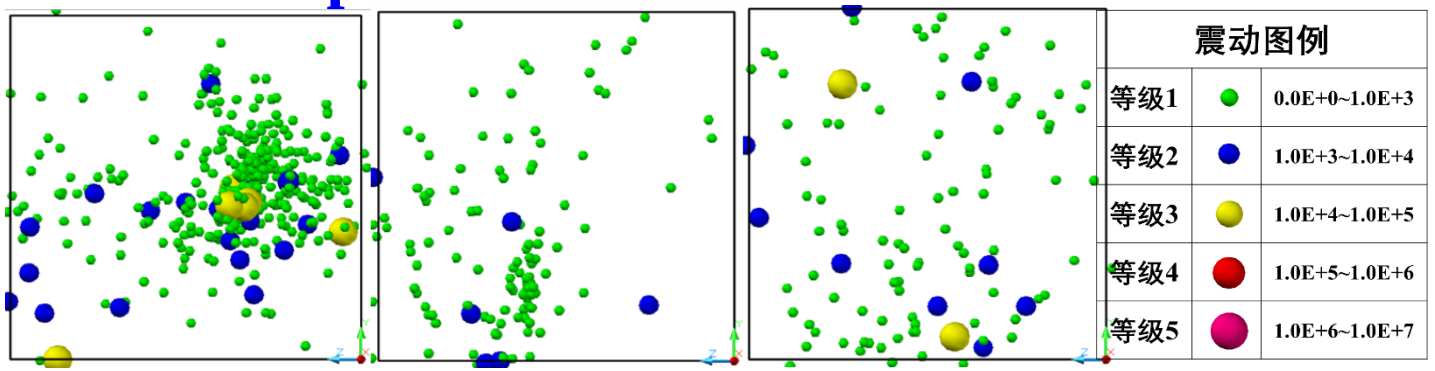
- **应力条件 Stress：**

<60MPa ，未冲击 non-butst

>60MPa ，冲击 burst

加卸载三轴应力转换特征
Characteristics of triaxial stress transformation under load-unload test

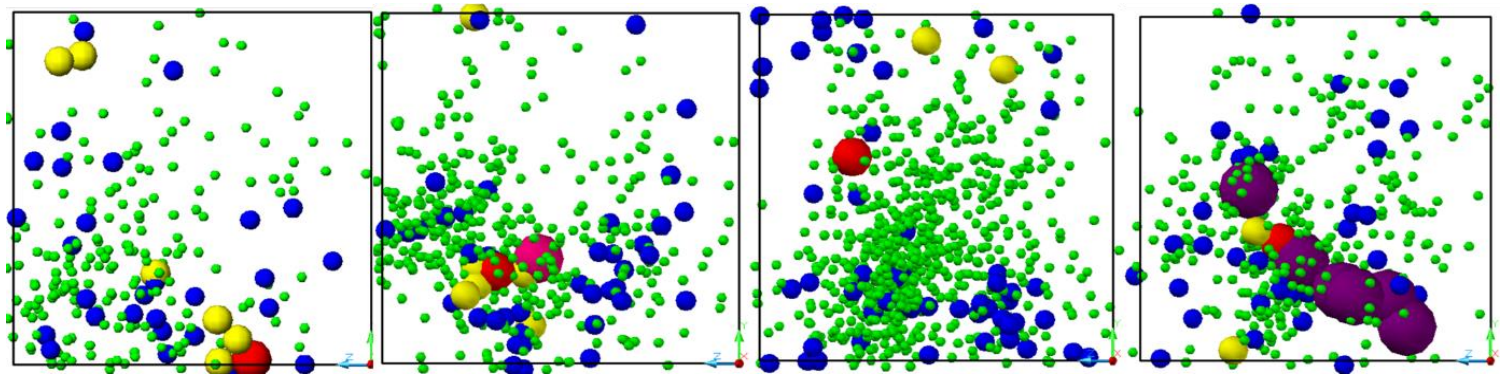
2.6 “加-卸”应力路径下煤样声发射特征 AE characteristics of specimens under stress path with load-unload-fix



● 未冲击 Non-burst：

Energy<1.0E+05μV·s

Ⅰ、Ⅲ、Ⅳ阶段ZY面事件定位图（试块C）AE event location map on Z-Y plane in Stages I, III and IV（Test block C）



● 冲击 Coal burst:

Energy>1.0E+07μV·s

Ⅰ、Ⅲ、Ⅳ阶段和高速卸载阶段ZY面事件定位图（试块M）

AE event location map on Z-Y plane in Stages I, III and IV and high-speed unloading stage （Test block M）

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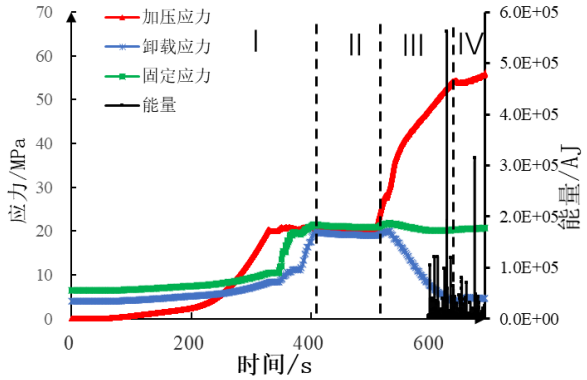
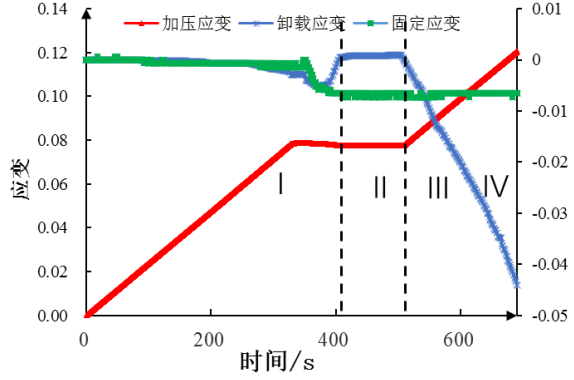
试样加卸载影响因素分析
Influencing factors for load-unload test of specimens

3.1 卸加比——径向卸载速率和切向加载速率的比值

Unloading-loading ratio：Ratio of radial unloading rate to tangential loading rate

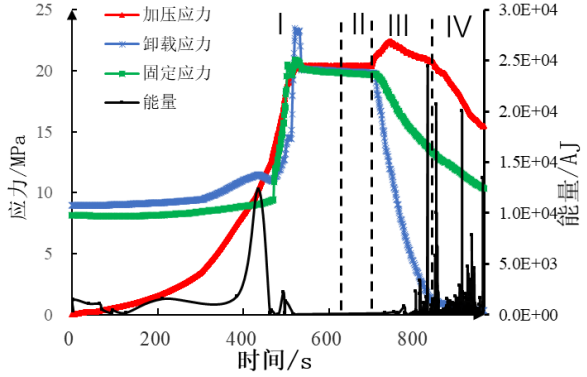
- 不同加载速率的应力应变曲线 Stress-strain curves at different loading rates

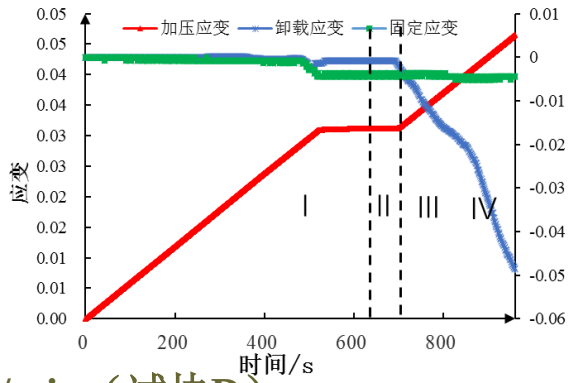




加载速率1.00mm/min（试块J）

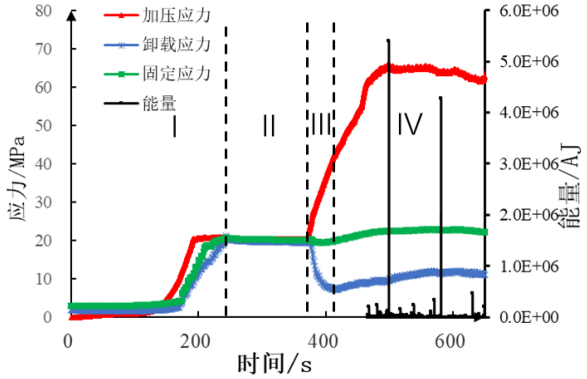
Loading rate 1.00 mm/min（Test block J）

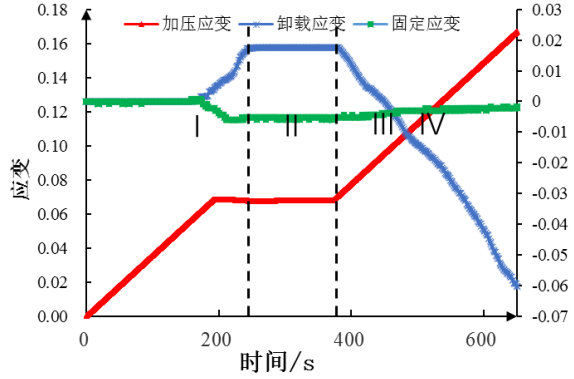




加载速率1.25mm/min（试块D）

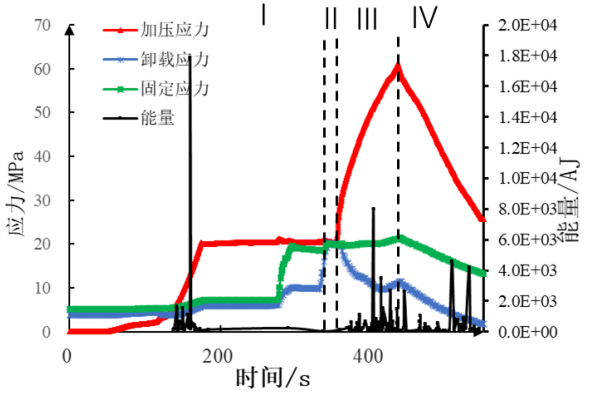
Loading rate 1.25 mm/min（Test block D）

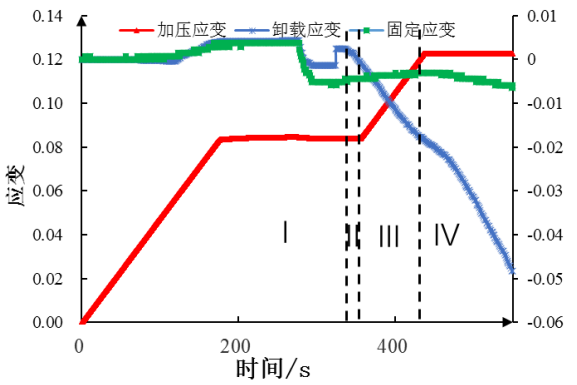




加载速率1.50mm/min（试块L）

Loading rate 1.50 mm/min（Test block L）





加载速率2.00mm/min（试块I）

Loading rate 2.00 mm/min（Test block I）

试样加卸载影响因素分析
Influencing factors for load-unload test of specimens

3.1 卸加比——径向卸载速率和切向加载速率的比值

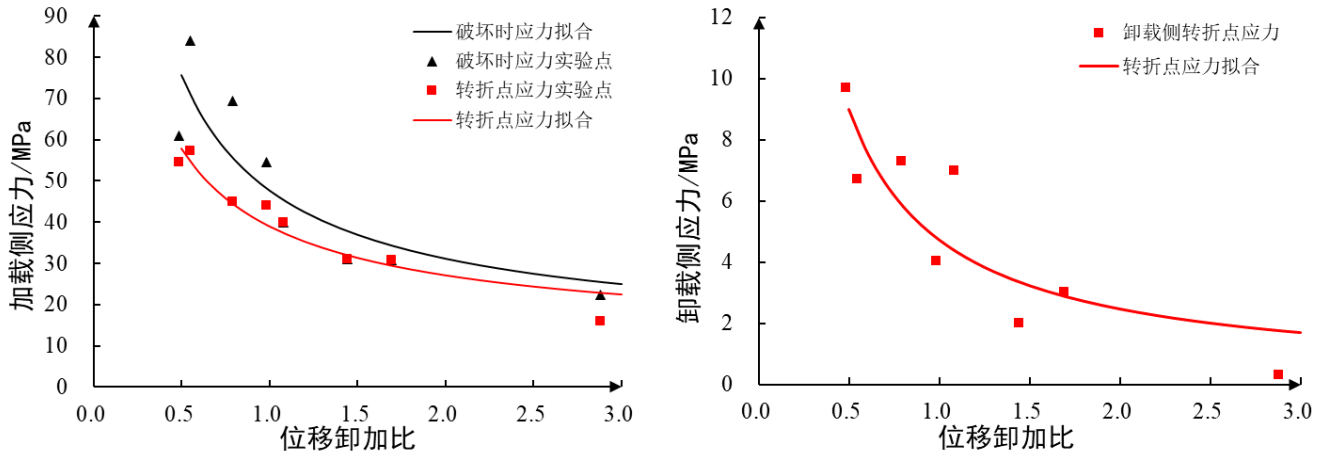
Unloading-loading ratio：Ratio of radial unloading rate to tangential loading rate

- 卸加比较高（即加载速率较低）时，固定侧的应力随卸载而降低；AE＜4×10^4aJ；
- When unloading-loading ratio was high (i.e.loading rate was low), the stress at fixed side decreased with unloading. AE＜4×10^4aJ

- 卸加比较低时，固定侧的应力增加；AE＞4×10^5aJ；
- When unloading-loading ratio was low, stress at fixed side increased. AE＞4×10^5aJ

- 固定侧应力增加或者降低的临界卸加比为0.8左右。
- The critical unloading-loading ratio for increase or decrease of stress at fixed side is about 0.8.

$$\sigma_{uturn} = 0.30 \cdot (\sigma_c - 8\frac{h'}{h'+1}) \cdot h'^{-0.81}$$



试样加卸载影响因素分析
Influencing factors for load-unload test of specimens

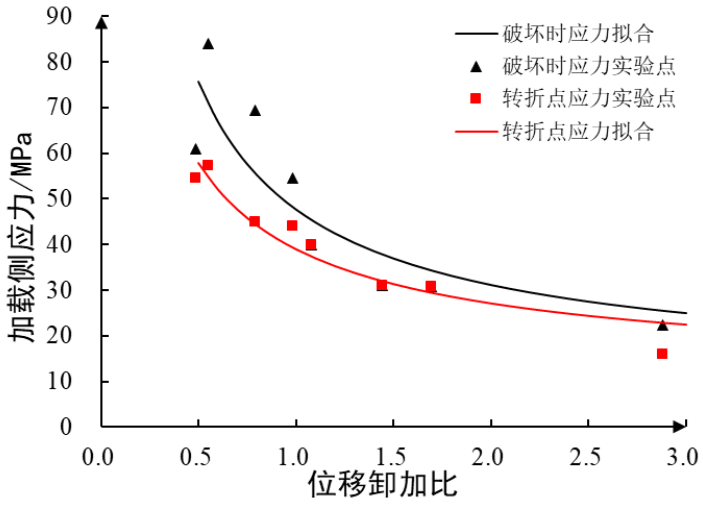
3.1 卸加比——径向卸载速率和切向加载速率的比值

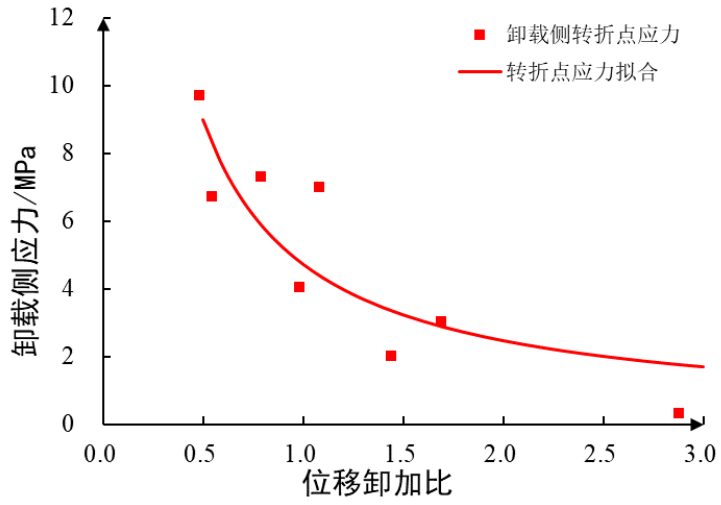
Unloading-loading ratio：Ratio of radial unloading rate to tangential loading rate

- **AE大能量处在弹性Ⅲ→塑性Ⅳ阶段转换**
- **High-energy AE events occurred during the transition from stage III(Elastic stage) to stage IV (Plastic stage).**

$$\sigma_{uturn} = 0.30 \cdot (\sigma_c - 8\frac{h'}{h'+1}) \cdot h'^{-0.81}$$

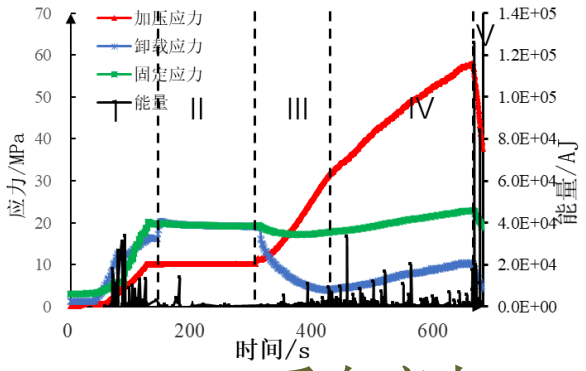
- **弹性区和塑性区转折点的应力随卸加比的增加而减小**
- **Stress at turning point of elastic zone and plastic zone decreased with the increase of unloading-loading ratio.**

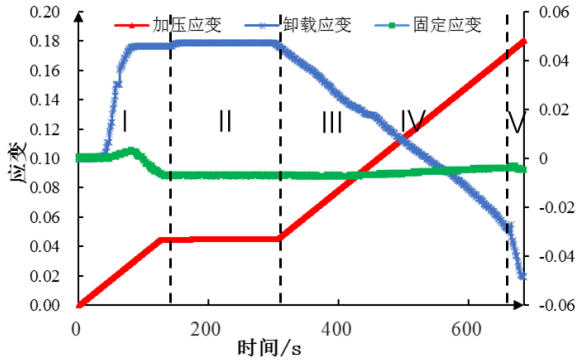




试样加卸载影响因素分析
Influencing factors for load-unload test of specimens

3.2 初始加载侧应力的影响
Initial stress at loading side

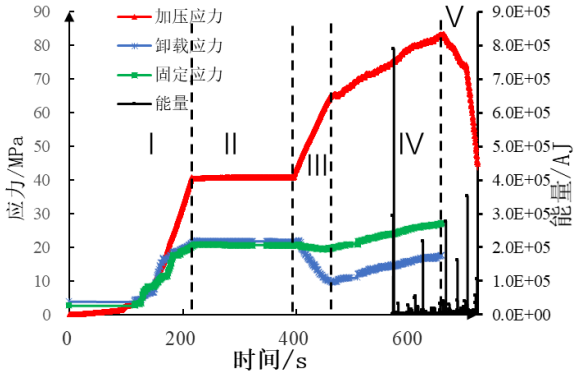


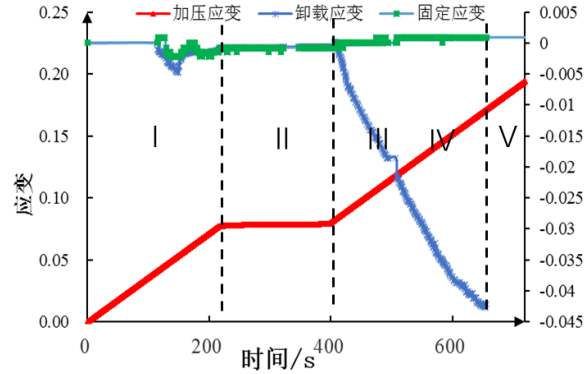


垂向应力10MPa（试块O）

Vertical stress 10 MPa（Test block O）

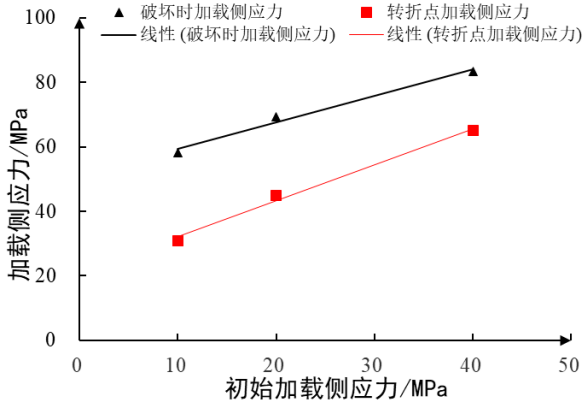
- 初始轴压较低，AE＜4×10^4aJ
- Lower initial axial compression: AE ＜ 4×10^4aJ
- 初始轴压较高，AE＞1×10^6aJ
- Higher initial axial compression: AE ＞ 1×10^6aJ

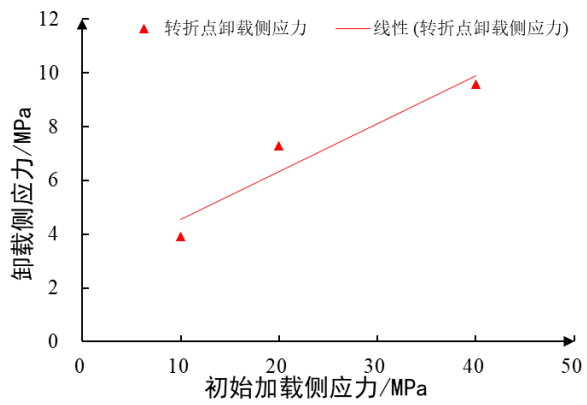




垂向应力40MPa（试块P）

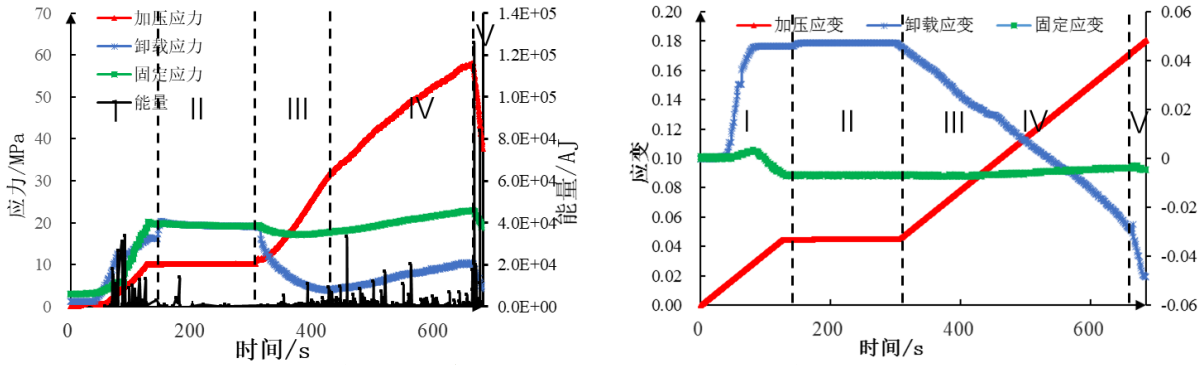
Vertical stress 40 MPa（Test block P）





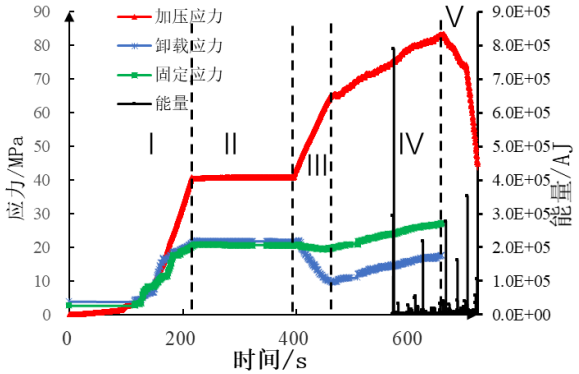
试样加卸载影响因素分析
Influencing factors for load-unload test of specimens

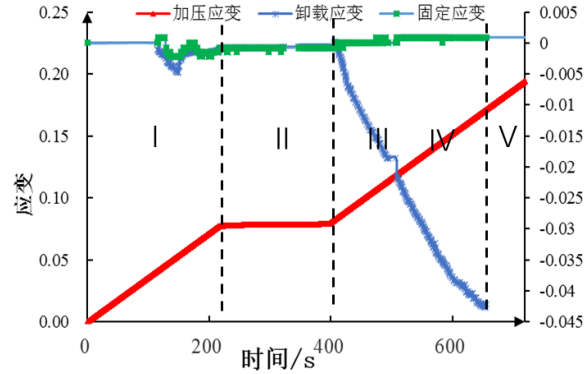
3.2 初始加载侧应力的影响
Initial stress at loading side



垂向应力10MPa（试块O）

Vertical stress 10 MPa（Test block O）

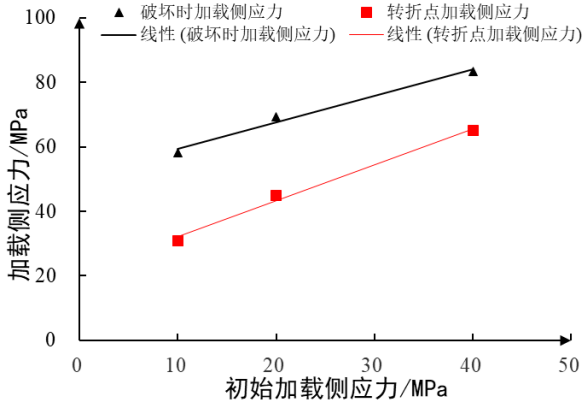


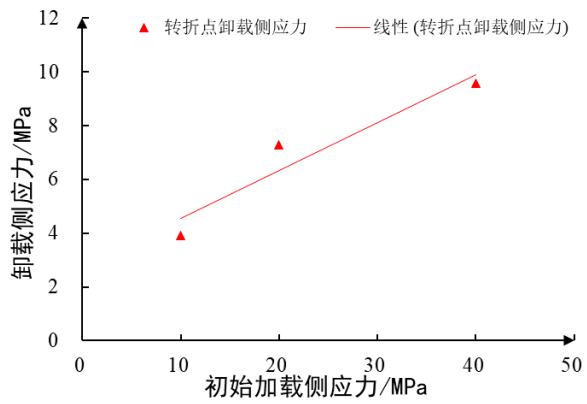


垂向应力40MPa（试块P）

Vertical stress 40 MPa（Test block P）

- 加载侧的峰值应力、Ⅲ→Ⅳ阶段转折点C处的应力随着初始竖向（加载侧）应力的增加而增加。
- Peak stress at loading side and stress at turning point C from stage III to IV both increased with the increase of initial vertical stress at loading side.
- 峰值应力和分界点应力的增加反映出冲击危险性的增加。
- The increase of peak stress and stress at turning point both reflect increase of coal burst hazard.

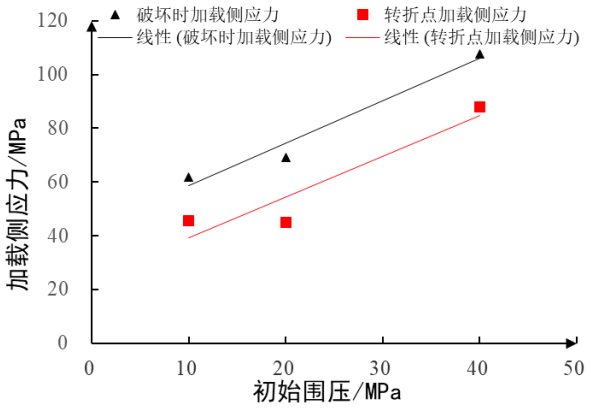


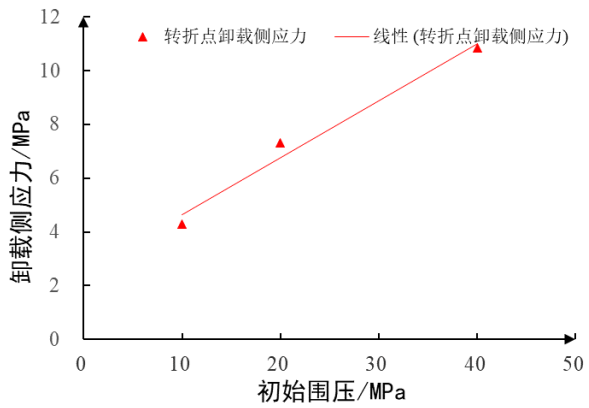


试样加卸载影响因素分析
Influencing factors for load-unload test of specimens

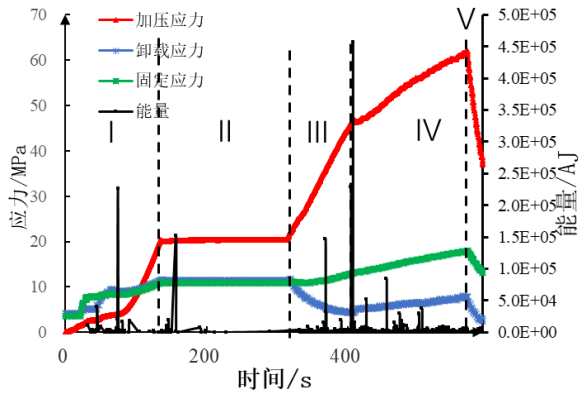
3.3 初始围压的影响
Initial confining pressure

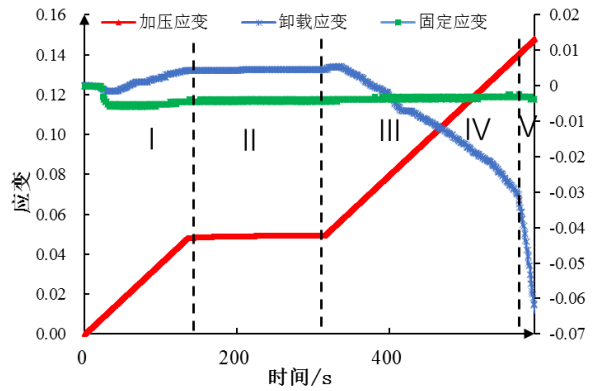
- 加载侧峰值应力、第Ⅲ阶段和第Ⅳ阶段转折点C处的应力均随着初始围压应力（包含卸载侧和固定侧应力）的增加而增加;
- Peak stress at loading side and stress at turning point C from stage III to IV both increase with the increase of initial confining pressure (including stresses at unloading side and fixed side).





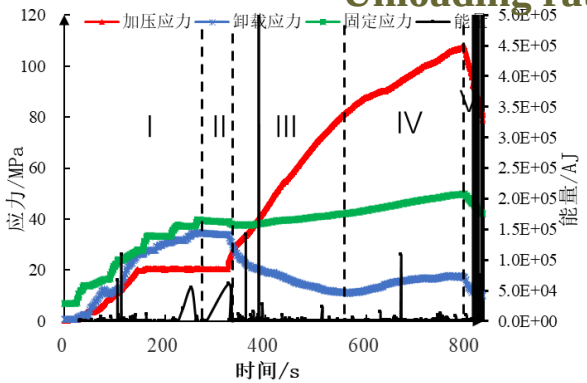
- 卸载侧应力和固定侧应力相同
- Stress at unloading side is the same as that at fixed side.

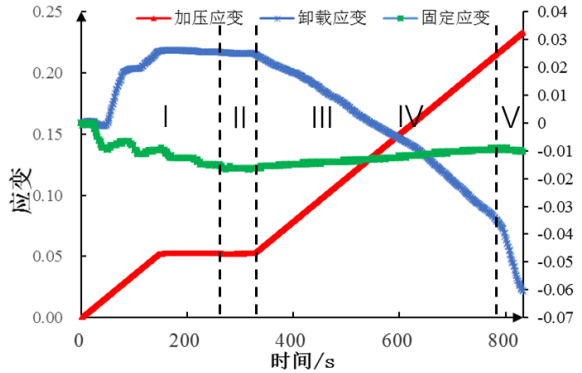




初始围压应力10MPa（试块N）卸载速率6.12mm/min

Initial confining pressure 10 MPa（Test block N）
Unloading rate 6.12 mm/min





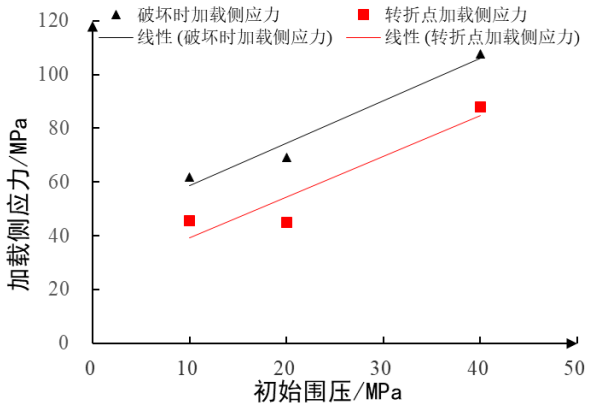
初始围压应力40MPa（试块M）卸载速率2.77mm/min

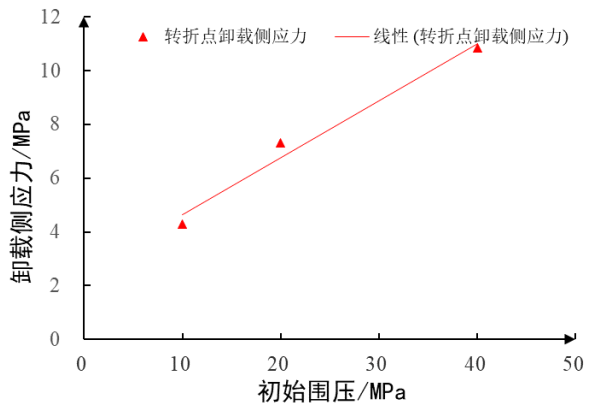
Initial confining pressure 40 MPa（Test block M）
Unloading rate 2.77 mm/min

试样加卸载影响因素分析
Influencing factors for load-unload test of specimens

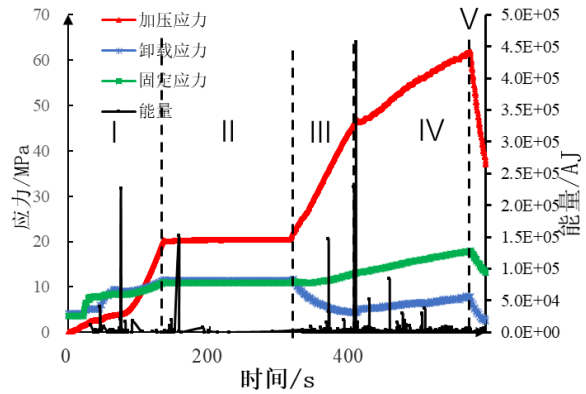
3.3 初始围压的影响
Initial confining pressure

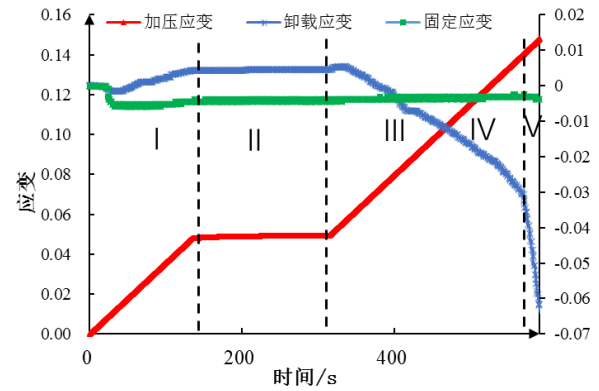
- 声发射事件主要位于第Ⅲ、Ⅳ、Ⅴ阶段
- AE events mainly occurred in stage Ⅲ,Ⅳ and Ⅴ.





- 卸载侧应力和固定侧应力相同
- Stress at unloading side is the same as that at fixed side.

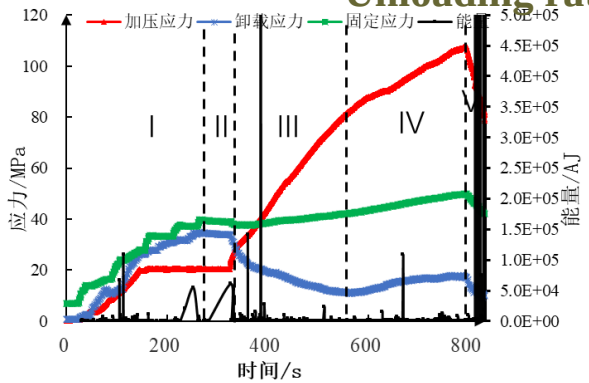


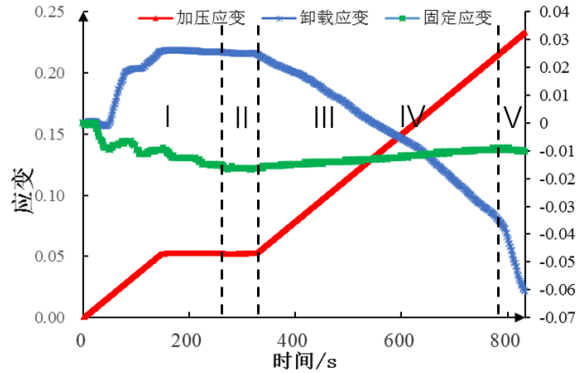


初始围压应力10MPa（试块N）卸载速率6.12mm/min

Initial confining pressure 10 MPa（Test block N）

Unloading rate 6.12 mm/min





初始围压应力40MPa（试块M）卸载速率2.77mm/min

Initial confining pressure 40 MPa（Test block M）

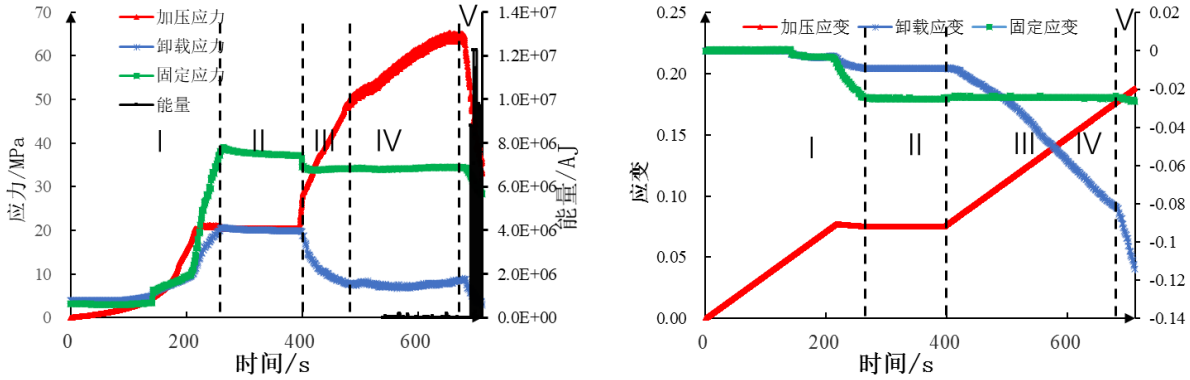
Unloading rate 2.77 mm/min

试样加卸载影响因素分析
Influencing factors for load-unload test of specimens

3.3 初始围压的影响
Initial confining pressure

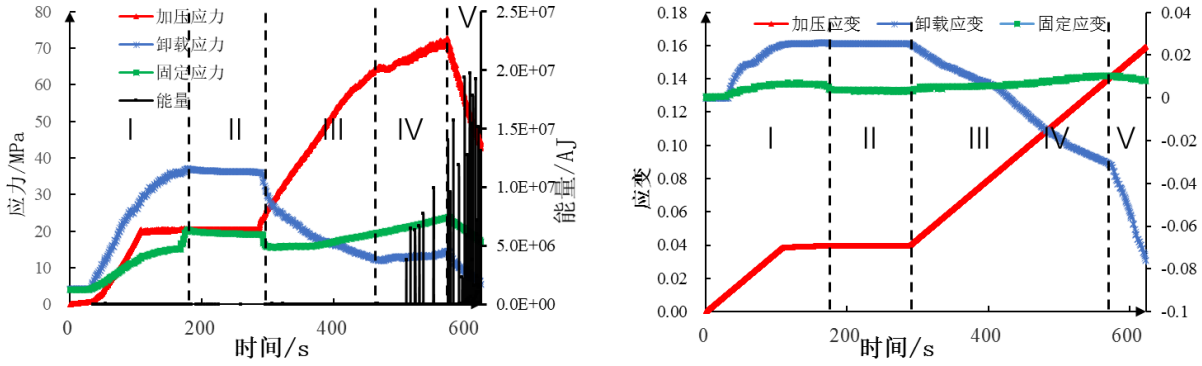
- 加载侧峰值应力、加载侧转折点应力、卸载侧转折点应力随着卸载侧应力的增加而增加，应力的增加反映出冲击危险性的增加。
- Peak stress at loading side, turning point stress at loading side and turning point stress at unloading side all increase with the increase of stress at unloading side. The increase of stress reflects increase of coal burst hazard.

- 卸载侧应力和固定侧应力不同
- Stress at unloading side was different from that at fixed side.



卸载侧初始应力20MPa，固定侧应力40MPa（试块R)

Initial stress at unloading side 20 MPa
Stress at fixed side 40 MPa（Test block R)



卸载侧初始应力40MPa，固定侧应力20MPa（试块Q)

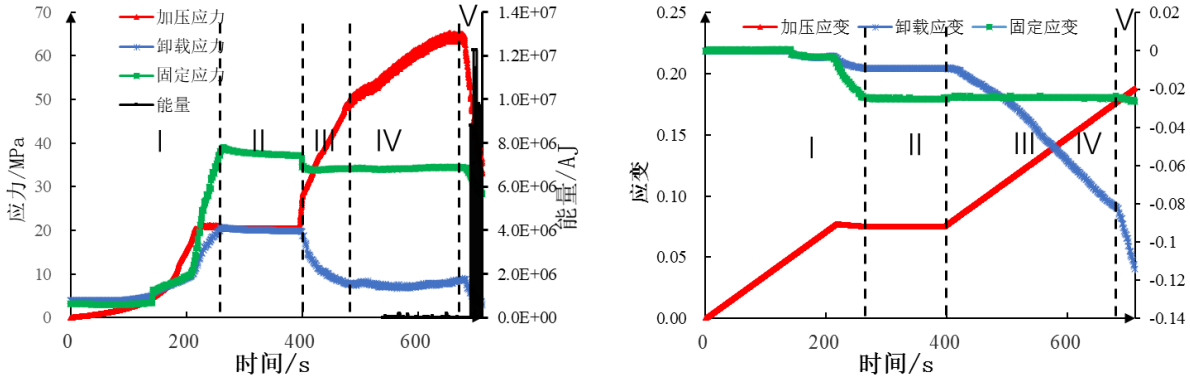
Initial stress at unloading side 40 MPa
Stress at fixed side 20 MPa（Test block Q)

试样加卸载影响因素分析
Influencing factors for load-unload test of specimens

3.3 初始围压的影响
Initial confining pressure

- 大能量声发射事件主要位于第Ⅴ阶段的高速卸载阶段，能量均达到1.0E+07aJ以上。
- High-energy AE events mainly occurred in stage V (high-speed unloading stage), and AE energies all exceed 1.0E+07aJ.

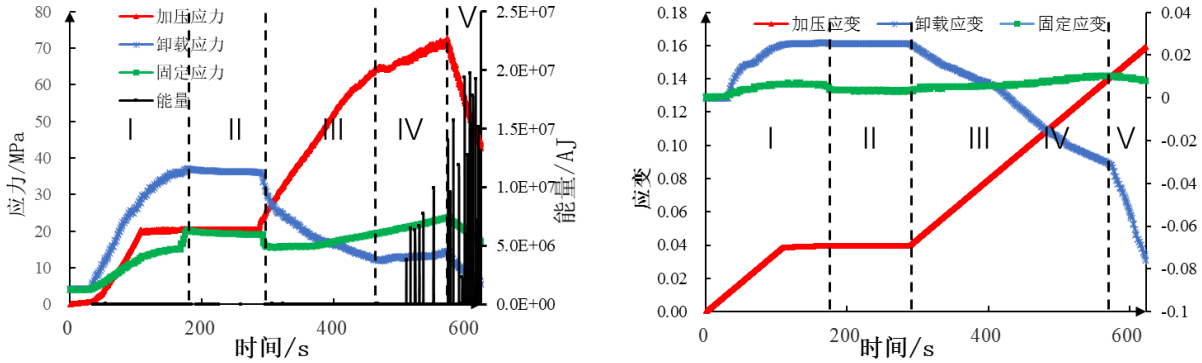
- 卸载侧应力和固定侧应力不同
- Stress at unloading side was different from that at fixed side.



卸载侧初始应力20MPa，固定侧应力40MPa（试块R)

Initial stress at unloading side 20 MPa

Stress at fixed side 40 MPa（Test block R)



卸载侧初始应力40MPa，固定侧应力20MPa（试块Q)

Initial stress at unloading side 40 MPa

Stress at fixed side 20 MPa（Test block Q)

Thanks!