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Study on the Failure Mechanism of Prefractured Coal Samples under Stepwise Cyclic Loading Based on PFC^{2D} Simulation

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Abstract: To investigate the dynamic instability of surrounding rock in mining faces caused by engineering disturbances in coal-rock masses with structural defects within gate roads, PFC^{2D} numerical simulation was employed to replicate laboratory tests, with its reliability verified. Further analysis was conducted on the development of microcracks, the evolution of displacement fields, and contact force chains under cyclic loading. Finally, the influence of pre-existing fractures on the fatigue damage evolution of coal samples under cyclic loading was elucidated. This study provides insights for reinforcing fractured coal masses and preventing dynamic hazards in mining excavations. The key findings of this study are as follows: For pre-fractured specimens, microcracks initially emerge at the tips of pre-existing fractures and subsequently propagate outward. These microcracks predominantly concentrate in the vicinity of the pre-fractures.

Keywords: Cyclic load; Defective coal sample; PFC^{2D}.

1. Introduction

According to the spatiotemporal relationship between the gateway and the working face [1], gateways can be classified into solid coal gateways, coal mass-coal pillar gateways, and non-pillar gateways (gob-side entry driving and gob-side entry retaining) [2].Throughout the entire lifecycle of the gateway, secondary fractures initiate and propagate in the surrounding rock under the influence of abutment pressure, gas drainage, and bolt drilling. Furthermore, periodic disturbances such as roof periodic fracturing [3], mechanical vibrations, and blasting [4] exacerbate fracture propagation, leading to reduced load-bearing capacity of the surrounding rock, bolt failure [5], and ultimately surrounding rock instability. Therefore, with the increasing intensity of coal mining, the rheological disturbance [6] and fatigue damage [7] of surrounding rock induced by cyclic loading cannot be ignored.

Laboratory tests have limitations in characterizing the complete evolution process of rock microstructures. Therefore, this study employs PFC2D numerical simulation to analyze the development of microcracks and the evolution of displacement fields and contact force chains in coal-rock under cyclic loading. The findings provide valuable references for understanding the stability of coal-rock masses under stepwise cyclic loading-unloading conditions.

2. Sample Preparation and Method

2.1. Sample preparation

The raw coal blocks used in the test were collected from Shendong mining area, exhibiting intact structure, homogeneous texture and no visible fractures on the surface.In accordance with MT38-48-87 ‘Methods for Determining Physical and Mechanical Properties of Coal and Rock’, the specimens were processed into standard cylindrical samples with a diameter of 50mm, height of 100mm, and end face flatness less than 0.02mm.According to relevant research findings, coplanar fractures exhibit the most significant influence on rock mass strength. Therefore, this study adopted pre-fabricated fractures with an inclination angle of α=45°, length 2a=10mm, and width 2b=0.5mm in the test specimens. As shown in Figure 1.

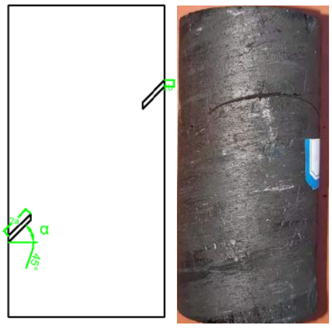

Figure 1. Sample specification

2.2. Experimental design

The average peak strength σ of the specimens was determined through conventional uniaxial compression tests, which was then used to establish the upper and lower limits for the stepwise constant-amplitude cyclic loading tests. Starting from an initial stress of 0 MPa, cyclic loading was applied in increments of 20% of the average peak stress (σ), with cyclic upper limits set at 20%, 40%, 60%, and 80% of σ. The upper stress limit of each loading cycle served as the lower stress limit for the subsequent stress level. Based on field monitoring data of mining truck loads, blasting, and tunnel excavation, along with relevant research findings , a cyclic loading frequency of 0.2 Hz was adopted in this test. To investigate the repeated loading-unloading process experienced by coal under multi-step/mining disturbance, 20 cycles were applied at each stress level. The stress path of the designed stepwise constant-amplitude cyclic loading test is illustrated in Figure 2.

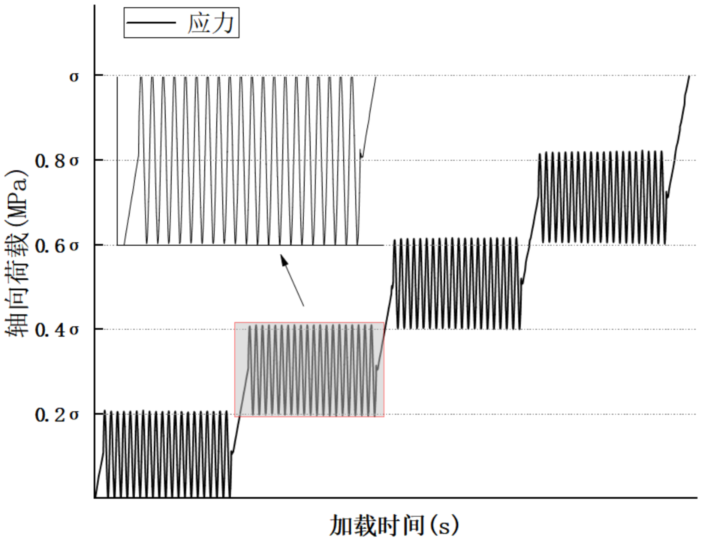

Figure 2. Axial load-time curve

3. Establishment of PFC^{2D} Particle Flow Model

The core workflow for establishing the particle flow model of stepwise constant-amplitude cyclic loading/unloading tests in this study mainly includes the following key steps: wall generation, particle generation, assignment of parallel bond contact model, stress initialization, and servo-controlled loading.

(1) Wall generation

The 'wall create' command generated four 50×100 mm walls, with dimensions slightly expanded to avoid particle leakage at joints. A 100 GPa normal stiffness was assigned to ensure boundary stability.

(2) Particle generation

Circular particles were generated using the 'ball distribute' command, followed by the 'cycle' command to achieve initial equilibrium. The model consists of 9,484 randomly distributed particles with diameters ranging from 0.3 to 0.45 mm. The system porosity is 0.10, and the particle density is set at 1.25 g/cm^3.

(3) Crack initiation and propagation

Pre-existing fracture walls were generated using the 'wall create vertices' command, and particles within these fracture walls were subsequently removed via the 'ball delete range polygon vertices' command.

(4) Parallel Bond Model (PBM)

The Parallel Bond Model (PBM) can effectively simulate the failure process of rock materials and characterize the bonding properties between particles. In this simulation, after completing PBM parameter assignment, the walls on both sides and around the pre-existing fractures were removed. The model formed a total of 24,805 contact points. However, in certain regions near the pre-existing fractures where particles contacted the walls, both contact stresses and unbalanced forces exhibited abnormally high values, indicating uneven stress distribution within the numerical specimen at this stage.

(5) Stress initialization

The "wall attribute yvelocity" command was used to apply pre-compression stress. By setting an appropriate pre-compression value, this approach not only realistically simulated the in-situ rock environment but also achieved uniform stress distribution among particles, effectively eliminating unbalanced forces in the numerical specimen. In the pre-existing fracture zone, the contact stress was significantly reduced, while distinct stress concentration phenomena were observed at the fracture tips.

(6) Servo loading mechanism

In the PFC simulation system, walls serve as massless boundaries that cannot directly apply loads to particles, but can only induce particle displacement through velocity control. To simulate complex multi-stage constant-amplitude cyclic loading/unloading conditions, a servo-controlled loading (Servo) algorithm was implemented via FISH functions. By dynamically adjusting the movement velocities of the upper and lower boundaries, this method achieved precise stress field control, effectively minimizing the deviation between theoretical and measured values.

The final model is shown in Figure 3:

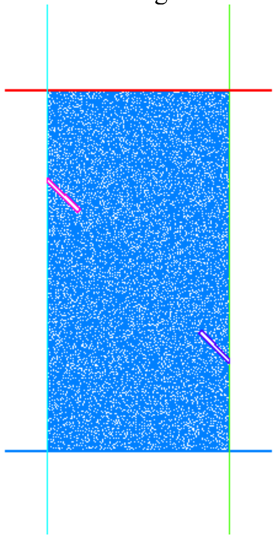

Figure 3. Schematic diagram of pre-existing fracture specimen model

4. Spacetime Evolution Analysis of Microcracks

As shown in Figure 4, in the numerical specimen with pre-existing fractures, microcracks predominantly concentrate at the upper and lower ends of the specimen, with relatively fewer cracks observed in the central region. Furthermore, for specimens containing pre-existing fractures, microcracks initially nucleate at the fracture tips and subsequently propagate outward. The majority of microcracks are localized in the vicinity of the pre-existing fractures.

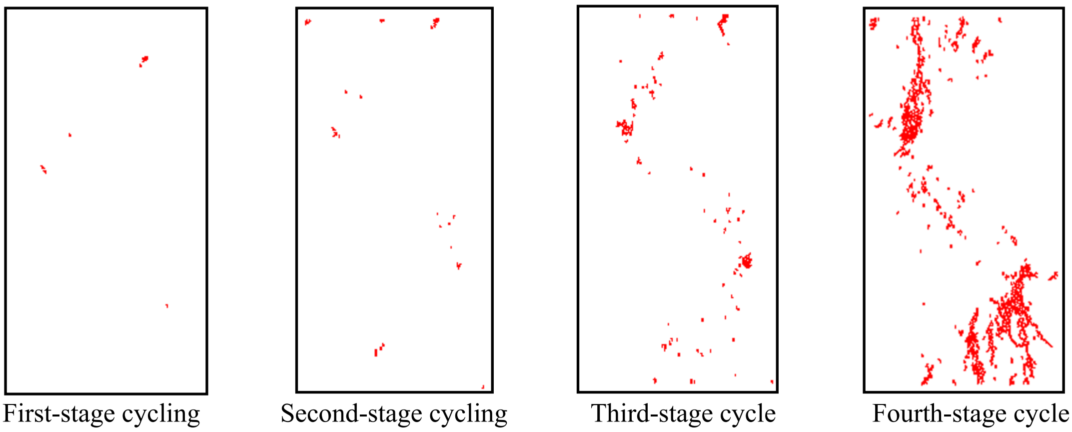
First-stage cycling Second-stage cycling Third-stage cycle Fourth-stage cycle

Figure 4. Crack propagation diagram of pre-existing fracture specimen

5. Summary

(1) For pre-fractured numerical specimens, internal microcracks are concentrated at the upper and lower ends, while relatively fewer cracks are observed in the middle section.

(2) For pre-fractured specimens, microcracks initially develop at the tips of pre-existing fractures and subsequently propagate outward, primarily concentrating near the pre-fractured zones.

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