

Compressive Behaviors of Ice with Different Strain rates: Multiscale Fracture Characteristics of Strength and Fragmentation

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Abstract

In ice mechanics, the strain rate-dependent properties of ice under uniaxial compression have attracted attention. In this work, the rate-dependent properties of polycrystalline ice are studied through experiments and numerical simulation. For the experimental part, uniaxial compression tests are carried out on polycrystalline ice with different strain rates. For numerical simulation, a discrete element numerical model based on grain is constructed, and the microscopic parameter calibration is completed. Ice compression at different strain rates is simulated by combining the mechanical properties of single-crystal ice and polycrystalline ice, and the simulation and experimental findings are mutually verified. The results show that the uniaxial compressive strength of polycrystalline ice increases exponentially with the strain rate. The ice samples break substantially at a high strain rate, and the average broken area is inversely proportional to the strain rate. In the crack initiation, propagation, and coalescence of polycrystalline ice, intergranular failure is dominant. In terms of crack type, tensile failure is dominant. On the basis of existing studies, a rate-dependent model of the uniaxial compressive strength of polycrystalline ice is proposed.

Keywords Strain rate effect; Fragment characteristic; Multiscale fracture; Discrete element method; Grain-based model

1 Introduction

The uniaxial compression of ice has gained significant attention, particularly in the fields of icebreaker navigation and aircraft landing in polar regions (Liu et al., 2023; Liu et al., 2021; Zhang et al., 2021a; Timco and Weeks, 2010; Sun et al., 2023; Taylor and Jordaans, 2015; Ni et al., 2020; Ji et al., 2020). Ice properties under uniaxial compression differ from those under multiaxial compression, thus requiring further research and understanding (Timco and weeks,

2010; Hawkes et al., 1972; Li et al., 2011; Schulson and Gratz, 1999; Schulson et al., 1984; Schulson, 1997; Schulson, 2001; Schulson, 2009; Timco and Frederking, 1986). Another fascination is how ice fractures under varying loading states directly influence the navigational conditions of ships in areas with fragmented ice within ice regions, especially at different loading rates. Thus, the mechanical properties of ice under various loading rates must be understood to improve the performance of aircraft landing and icebreaker navigation and ensure safety.

Therefore, a comprehensive understanding of the rate correlation of ice is useful in providing references for the construction of structures in polar regions (Liu et al., 2023; Liu et al., 2021; Di et al., 2017; Lu et al., 2018). Large-scale simulations or experiments directly provide information for the design and fabrication of structures in polar regions; however, they are often constrained by various limitations, such as experimental equipment and expensive test costs. Many researchers find it advantageous to study ice failure on a laboratory scale (Yuan et al., 2022; Zhang et al., 2020; Zhang et al., 2021a). Fully understanding ice failure at a low scale will allow us to construct a reasonable explanation of ice failure at the engineering scale. It will also simplify upscaling the findings and offer comprehensive insights into manufacturing structures in polar regions. In the study of ice failure at a laboratory scale, significant progress has been made in experimental techniques

Article Highlights

- Based on the real grain structure, a numerical mechanical model of polycrystalline ice was established using the discrete element method (DEM).
- With the change of strain rate, the proportion of grain boundary failure and transgranular failure increases, and grain boundary failure is dominant.
- Through combining simulation and experiments, the uniaxial compressive strength of ice increases exponentially with the strain rate within the brittle strain rate range.
- The failure mode of polycrystalline ice shows a transformation from splitting to crushing with the increase of strain rate.

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and numerical simulation approaches.

To study the uniaxial compression of polycrystalline ice, a rate-dependent model describing the changes in the uniaxial compressive strength (UCS) of polycrystalline ice with strain rate must be established. Ice exhibits different properties under different loading rates. However, the UCS changes of polycrystalline ice with varying strain rates are still controversial. Cole et al. (1995) noted that the UCS of polycrystalline ice is independent of the strain rate in the range of 10^{-2} /s to 10^{-1} /s. Based on their test results for the uniaxial compression of polycrystalline ice, Jones (1997) pointed out that with the increase in strain rate, the UCS of polycrystalline ice continues to increase or remains stable. With a further increase in the loading rate to more than 10^{-1} /s, polycrystalline ice changes from splitting failure mode to crushing failure mode, and its UCS gradually increases with the increase in uniaxial strain rate. They also tested the UCS of polycrystalline ice at high-rate intervals of uniaxial strain and found that it is proportional to the strain rate. Carney et al. (2006) studied the impact failure of polycrystalline ice and found that when the strain rate changes from 98/s to 822/s, the UCS significantly increases with the strain rate. At high rates, the final failure mode of the sample is fragmentation. Shazly et al. (2009), Shafrova and Høyland (2008), and Kim and Keune (2007) conducted uniaxial compression tests at high rates and found that the UCS of polycrystalline ice increases with the loading rate at different temperatures.

Numerical simulation methods can capture fine-scale failure and uncover previously unnoticed observations that may be challenging to identify in laboratory experiments. These methods enhance our understanding of ice failure and fracture, allowing for a comprehensive analysis that complements traditional experimental approaches. Numerous techniques, including the cohesive element method (Gribanov et al., 2018a; Gribanov et al., 2018b), peridynamics (Lu et al., 2020; Li et al., 2023), and the discrete element method (DEM) (Sun et al., 2023; Prasanna et al., 2022), have been developed to analyze the numerical aspects of brittle failure in polycrystalline ice. These methods establish numerical models of polycrystalline ice based on the grain scale and reproduce the mechanical response of polycrystalline ice under certain loading conditions at a certain level. Gribanov et al. (2018a, 2018b) simulated the brittle failure of granular ice using the cohesive element method and found that the numerical model of polycrystalline ice can simulate the brittle failure of samples with different grain sizes. The results are in good agreement with the experimental results. Li et al. (2023) employed peridynamics to model the progression of tensile fractures in S2 columnar ice, establishing the smallest grain count within the specimen necessary to achieve isotropy. Sun et al. (2023) applied the DEM to simulate the brittle fracture of polycrystalline ice and found that the microscopic fracture characteristics

of specimens differ under confined pressures. Prasanna et al. (2022) established a 3D model of columnar ice using HiDEM and investigated the force transmission through fragmenting materials under compression. Although they were able to reproduce the brittle failure process of polycrystalline ice under specific loads, the failure process and rate-dependent response of ice materials under different strain rates were poorly reflected. As an important mechanical property of ice, the rate-dependence of UCS warrants further research.

In this work, the fracture process of polycrystalline ice is reproduced using a numerical model, which matches the laboratory test results. The rate-dependent effects of polycrystalline ice are discussed through the evolution of microscopic cracks, internal energy, and fragmentation characteristics.

2 Experimental setup and results

2.1 Ice materials

Polycrystalline ice samples were collected from various locations in the Songhua River, China, as illustrated in Figure 1. January 2023 was selected as the collection date when the ambient temperature was within the range of $-25\text{ }^{\circ}\text{C} \pm 3\text{ }^{\circ}\text{C}$. The temperature of the laboratory where the ice samples were prepared was regulated to match the environmental temperature at the time of collection. In this study, the orthotropic columnar ice was horizontally loaded (along X_1 or X_2) as shown in Figure 2. The grain size of the ice sample was approximately 6–10 mm, and the average density was approximately 898 kg/m^3 . The average grain size of polycrystalline ice was examined using an equivalent area method, which simplified the grain shape to a relatively regular hexagon and allowed for grain size measurement.

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2.2 Unconfined compressive tests

A mechanical material testing machine was utilized to conduct unconfined compressive tests on polycrystalline ice. The ice specimens were stored in a refrigeration unit maintained at a constant temperature, where the original ice was processed to the desired size. Following recommendations, rectangular specimens with a length of 175 mm and a 70 mm $\times$ 70 mm bottom were prepared. The unconfined compressive tests were conducted with applied strain rates ranging from 10^{-4} /s to 6/s. As shown in Figure 3, the uniaxial compression experimental setup system included a camera, a testing machine, and a low-temperature experimental box that maintains a low-temperature experimental environment.

Measuring 70 mm $\times$ 70 mm $\times$ 175 mm, the test specimens



Figure 1 Sampling location of ice specimens from the Songhua River



Figure 2 Polycrystalline ice's geometric structure and the method for equivalent crystal area

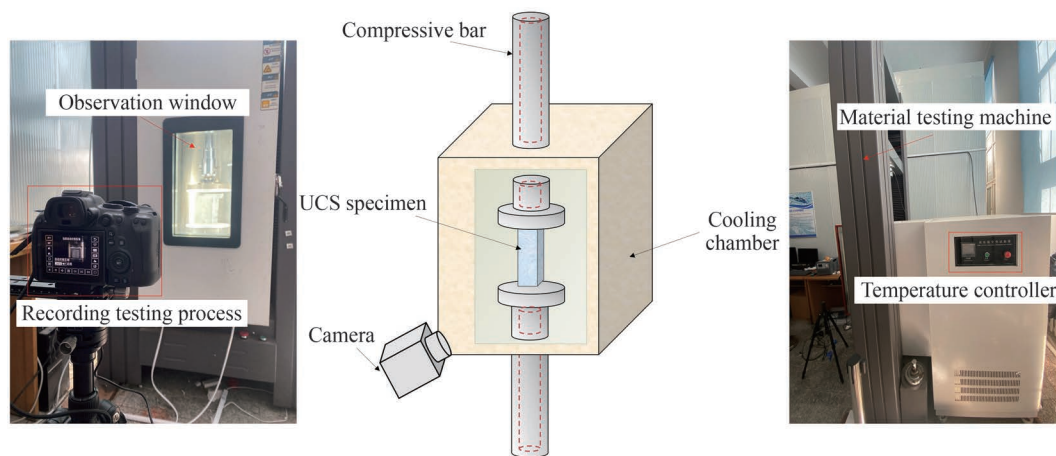


Figure 3 Setup and schematic of the unconfined compressive test system and cooling chamber

were meticulously placed at the central location of the loading plate. Experimental videos were diligently recorded using high-quality cameras to successfully capture the fracture and failure of the ice during loading. Furthermore, the specimens that failed during the experiment were dutifully saved and meticulously documented to showcase the diverse failure modes of the samples. The stress-strain curves of the specimens were computed by processing the axial experimental data captured during the experiment using state-of-the-art computation and recording techniques. Each experiment was deliberately repeated and reviewed after processing the data for the previous experiment, ensuring that the overall experiment was conducted with utmost accuracy and precision. The cooling chamber's temperature fluctuated within 2 °C of the test temperature using a cooling risk control system, and its interior was dried prior to the experiment.

The experiment proceeded with meticulous precision and accuracy, as the stress and strain values of the ice were determined through a series of carefully orchestrated calculations involving the calculation of force and displacement. In particular, the loading force F_{bar} applied to the ice from the compressive bar was calculated. In addition, the displacement of the upper loading plate, L_d , was dutifully recorded and analyzed. The experimental setup entailed fixing the lower loading plate while the upper loading plate was intentionally manipulated to ensure that all the necessary data points and measurements were collected with utmost accuracy and precision:

$$\sigma_c = \frac{F_{\text{bar}}}{A} \quad (1)$$

where σ_c is the stress of ice, A (4 900 mm²) is the bottom

area of the specimen, and the strain of the specimen was defined as

$$\varepsilon_c = \frac{L_d}{L} \quad (2)$$

where ε_c is the strain of the specimen, and L is the length of the specimen, i.e., 175 mm. The strain rate was set by the ratio of the loading rate and the length of the specimen:

$$\dot{\varepsilon}_c = \frac{v_d}{L} \quad (3)$$

where v_d is the loading rate for the compressive bar.

The UCS of ice was determined as the peak value on the stress-strain curve, and the Young's modulus was the stress-strain curve's slope. The Young's modulus was calculated using equation (4):

$$E = \frac{\Delta\sigma_c}{\Delta\varepsilon_c} \quad (4)$$

where $\Delta\sigma_c$ and $\Delta\varepsilon_c$ are the stress variation and uniaxial strain variation values, respectively, from the chosen part in Figure 4.

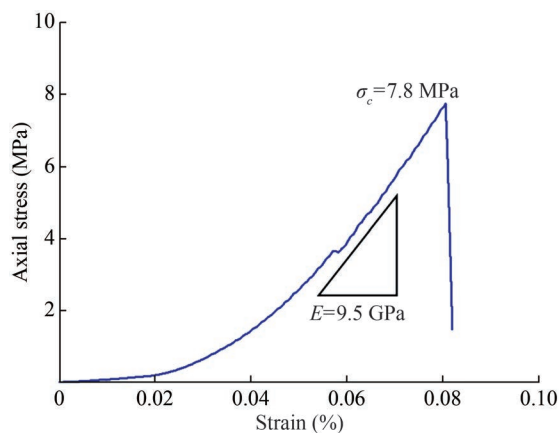


Figure 4 Stress-strain curve ($2.3 \times 10^{-1}/s$) obtained from the experiment

Throughout the testing phase, the ice specimens were compressed diametrically using an incredibly flattened platen to ensure that a constant strain rate was maintained throughout the experiment. As part of the experiment, we found that the elastic modulus of the columnar ice was 9.2 GPa on average, showcasing its robust nature and composition. Furthermore, our meticulous and detailed experimental tests revealed that the unconfined compressive strength of the ice was hugely reliant and dependent on the strain rate, showing its complex nature and how it interacts with various levels of stress and pressure.

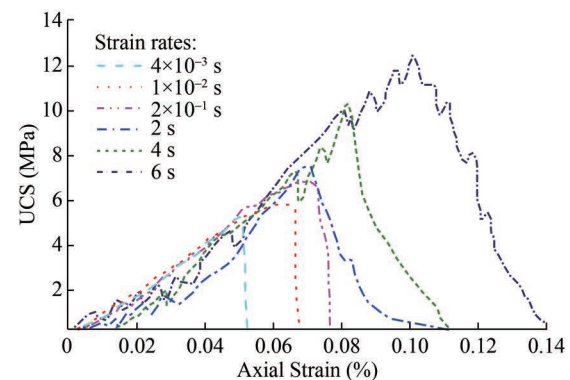
In specific instances, the unconfined compressive strength of the ice ranged from 5 to 12 MPa, underscoring the intricate nature of our experimental results. In the following section (Section 2.3), the observed phenomena were further investigated, and our experimental results were dis-

cussed in detail to provide a granular and holistic understanding of our research findings.

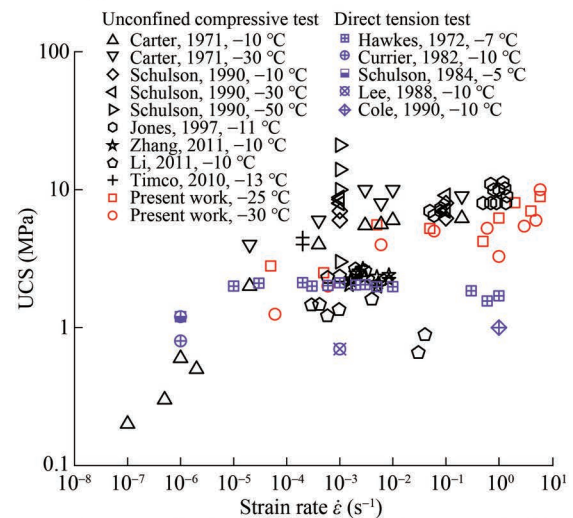
2.3 Fracture behaviors of columnar ice

The unconfined compression experiments of ice at different strain rates were conducted at temperatures ranging from -25°C to -30°C . Stress-strain curves were obtained from the experiments to capture the damage process of the ice under different strain rates. The stress-strain curves acquired from the experiments under different strain rates are listed below. Meanwhile, the unconfined compression values obtained from the experiments were summarized in the compiled experimental database of freshwater ice, which also includes test results from various scholars who also conducted experiments on this type of ice.

On the basis of the analysis of the experimental curves in Figure 5(a), the initial stage of the curves exhibited a slow rise due to the effects of the servo loading instrument and the compaction of the specimen. Afterward, the slope stabilized in the linear elastic stage, causing the UCS to



(a) Stress-strain curves under different strain rates



(b) Unconfined compressive strength compared with experiments in fields

Figure 5 Original experimental results and unconfined compressive strength obtained from laboratory tests

peak, followed by a sudden drop in the experimental curve. With the continued increase in loading rate, the stress-strain curve displayed a serrated pattern. The strain rate of the experimental loading in the present study corresponds to the range of ice brittle strain rates in the literature (Timco and Weeks, 2010; Hawkes and Mellor, 1972; Li et al., 2011; Schulson et al., 1984; Carter, 1971; Cole et al., 1995; Jones, 1997; Schulson, 1990; Zhang et al., 2011), as shown in Figure 5(b), which is consistent with the current research subject of ice brittle fracture. When the strain rate exceeded $10^{-3}/s$, the UCS of ice increased with the strain rate and exhibited significant strain rate dependence. This observed trend aligns closely with existing data and the current experimental findings.

Visual representations of the ice specimen's failure process during the experiments are provided in Figure 6 for further understanding. The failure processes of the specimens in the experiment were used as examples to describe the failure process. The specimens underwent significant crack initiation, propagation, coalescence, and fragmentation under axial compressive loading.

As depicted in Figure 6, the failure process of ice material at a strain rate of $2 \times 10^{-2}/s$ was meticulously recorded and described as follows: in stage a, an initial crack nucleated inside the ice material, as indicated by the red arrow. In stage b, the propagation of the initial crack extended from the bottom of the specimen toward the middle, at an angle of approximately 40° concerning the loading direction. The crack propagation was marked by the appearance of striations and markings on the surface of the specimen. In stage c, with the progression of crack propagation, multiple crack branches propagated inside the ice, forming addi-

tional cracks. The combination of the propagated crack and the crack branches in stage c led to the development of multiple split cracks inside the ice, as shown in stage (d). These fissures penetrated the entire specimen, culminating in the brittle failure and fragmentation of the ice into multiple pieces. Finally, the pieces of the fragmented ice specimen were carefully collected and analyzed to determine the failure mode as presented in Figure 6(e).

After the uniaxial compression experiments performed on freshwater polycrystalline ice from the Songhua River, the stress-strain curves and crack propagation failure processes were recorded for ice specimens subjected to different strain rates, along with the failure mode of the ice samples preserved for further analysis. In the following sections, a 2D numerical model of columnar ice was established based on the geometric morphology and mechanical properties of polycrystalline ice at the grain scale. The underlying mechanisms governing the failure of polycrystalline ice were investigated using experimental observations and numerical simulations.

3 Modeling of polycrystalline ice with GB-DEM

The numerical simulations presented in this paper were conducted within the DEM framework based on the grain scale properties of ice (GB-DEM). DEM is a numerical technique initially introduced by Cundall (Cundall, 1971; Cundall and Strack, 1979) and has gained extensive application in modeling complex systems, such as granular materials and rock-like materials (Di et al., 2017; Gao et al., 2016; Li et al., 2018; Li et al., 2021; Peng et al., 2017; Peng et al., 2018a).

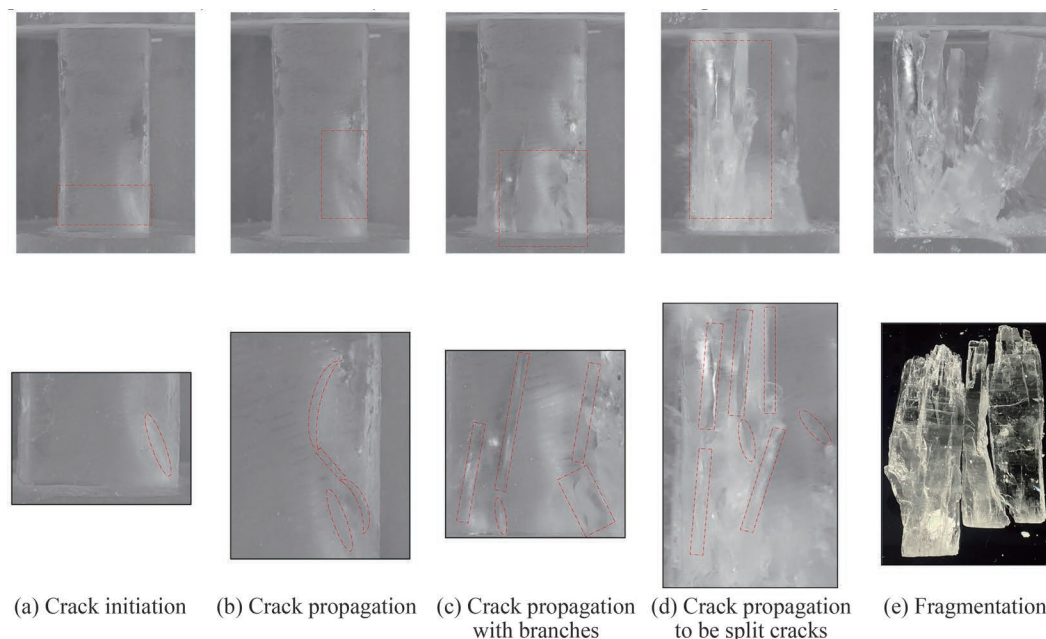


Figure 6 Fracture process and ultimate failure modes of ice specimens

3.1 Geometric modeling for polycrystalline ice

The procedure for geometrically modeling polycrystalline ice can be summarized as follows: the geometric model of polycrystalline ice was established using an embedded Voronoi method. First, random particles were distributed within a 70×175 mm 2D specimen, and their centers served as seeds to generate Voronoi-based grain boundaries with an average size of 8 mm (Figures 7(a)–7(d)). The model was then filled with discrete element particles (Figures 7(e)–7(f)). For the systematic analysis of mechanical interactions in the ice microstructure, contacts between particles within the same Voronoi grain were defined as transgranular (TG) contacts, and those at adjacent grain boundaries were classified as intergranular (IG) contacts. As shown in Figure 8, parallel bonds (PBs) were assigned to TG and IG contacts. The microscopic parameters of these PBs will be specified in subsequent sections. Upon fracture, the failed PBs degraded into visible cracks, enabling the direct visualization of crack propagation within the model.

In this section, the PB model between adjacent particles was utilized to investigate the mechanical properties of polycrystalline ice. Upon the generation of the geometric model, the PB model must be assigned to the particles' contacts. Figure 8 delineates the TG and IG classifications

within the framework of GBM, presenting the geometric representation of the PB model between two particles and illustrating the visual manifestations of IG and TG cracks within the specimen.

3.2 PB contact model

PB contacts can be conceptualized as a set of springs that are distributed uniformly over a rectangular cross-section at the contact plane. Bonds are susceptible to breaking under tension and shear. Figure 8 depicts the PB model that connects two particles, thus facilitating stress transfer and rotational momentum. The subsequent adjustments to the perpendicular and parallel forces associated with the PB interaction were executed as follows:

$$\bar{F}_n := \bar{F}_n + k_n \bar{A} \Delta \delta_n \quad (5)$$

$$\bar{F}_s := \bar{F}_s + k_s \bar{A} \Delta \delta_s \quad (6)$$

where k_n and k_s are the normal and shear stiffness values, respectively; $\Delta \delta_n$ and $\Delta \delta_s$ are the displacement increments; $\bar{A}$ is the cross-sectional area:

$$\bar{A} = 2\bar{R}, \bar{R} = \min(R^1, R^2) \quad (7)$$

where R^1 and R^2 are the radii of adjacent particles.

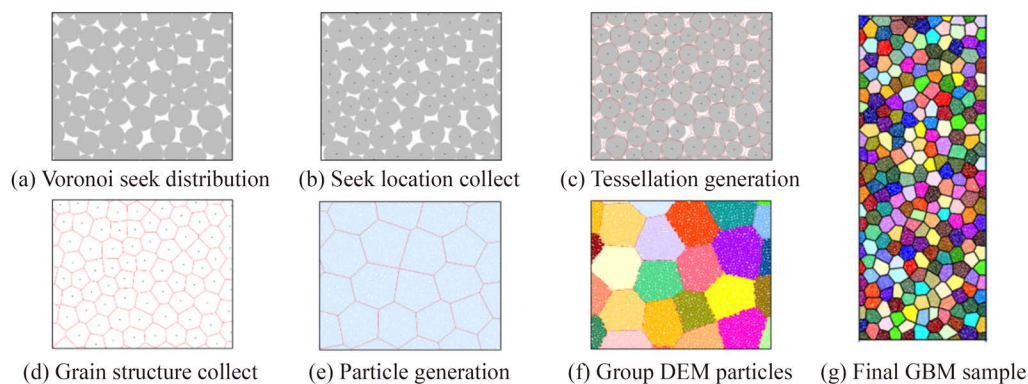


Figure 7 GBM model's generation process for polycrystalline ice

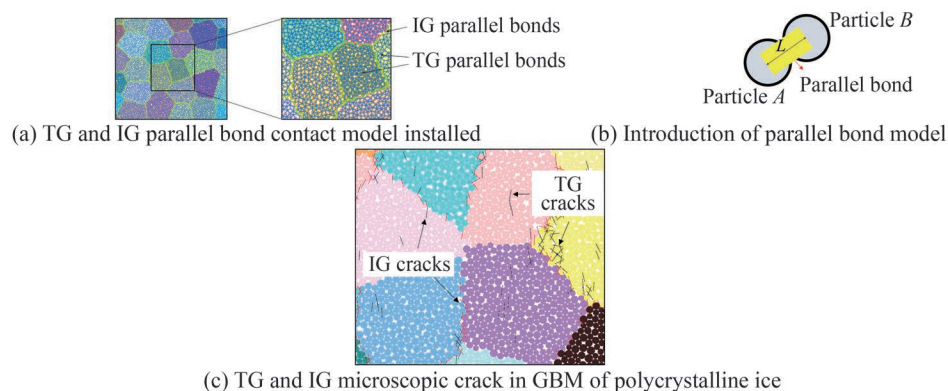


Figure 8 Elements in the GBM model

Let L be the length of PB associated with two particles with P^1, P^2 center positions

$$L = |P^1 - P^2| \quad (8)$$

k_n and k_s are the normal and shear stiffness values that can be determined as

$$k_n = \frac{EL}{\bar{A}} \quad (9)$$

$$k_s = \frac{k_n}{\lambda} \quad (10)$$

where E is the modulus of the bond.

$$\sigma_n = \begin{cases} k_n u_n, & \sigma_n \leq \sigma_t \\ 0, & \sigma_n > \sigma_t \end{cases} \quad (11)$$

where u_n is the normal displacement, and σ_n is the normal stress of the PB contact. When the normal stress σ_n exceeds the tensile strength of bond σ_t , the bond contact fails due to the tension. In the shear direction, the shear stress τ is determined by Coulomb sliding:

$$\tau = k_s u_s \quad (12)$$

where k_s is the shear stiffness, and u_s is the displacement in the shear direction. When τ exceeds the maximum shear strength $\tau_{\max}$, the bond contact fails by shear:

$$\tau_{\max} = \begin{cases} c_{\text{coh}} - \sigma_n \tan \varphi, & \sigma_n \leq 0 \\ c_{\text{coh}}, & \sigma_n > 0 \end{cases} \quad (13)$$

where c_{coh} is the cohesive strength, φ is the friction angle, and σ_n is the normal stress. After the failure of the PB, the contact model degenerates into a linear contact model with no cemental properties, and only Coulomb friction occurs in the shear direction:

$$\tau = \mu \sigma_n \quad (14)$$

where μ is the frictional coefficient between particles.

The PB contact model can be installed on a ball-ball contact by referring to the gap parameter g_c , which is defined as

$$g_c = L - (R^1 + R^2) \quad (15)$$

During the simulation, separate contact parameters for these two contact groups (TG and IG) were assigned to precisely describe the behavior of the polycrystalline ice under deformation and fracture. Four typical fracture modes at the grain scale are shown in Figure 9. Similarly, TG and IG microscopic cracks are shown in Figure 8c, and the breakage type (tension or shear) was determined through model calculation. In summary, the proposed method pro-

vides a powerful tool for investigating the fundamental mechanisms of deformation and fracture in complex materials such as polycrystalline ice.

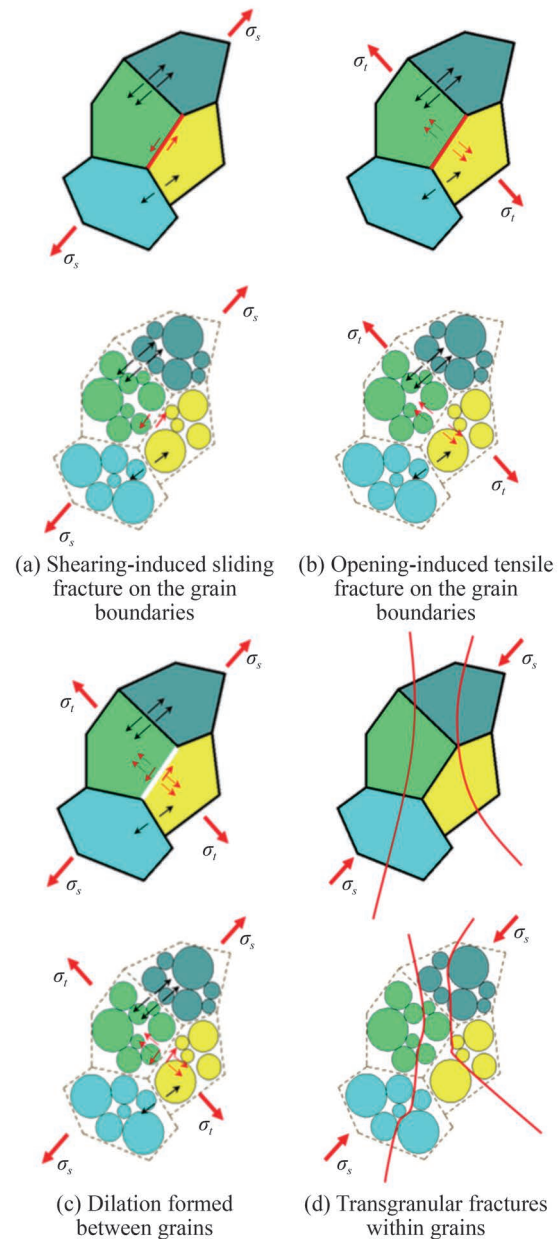


Figure 9 Typical failure modes of ice grains

Figure 10 is a diagram of particle motion along the normal and tangential directions during the tensile or shear failure of PBs. Under external forces, the cracks generated by particle failure along the normal direction are termed tensile cracks, and those formed by failure along the tangential direction are termed shear cracks. In practical simulations, particles within the specimen typically exhibit mixed motion along normal and tangential directions. Individual cracks were classified as tensile or shear according to which

failure mode (tensile or shear) occurs first.

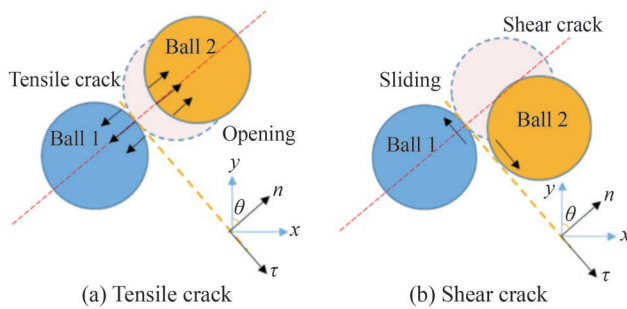


Figure 10 Diagram of parallel bond cracks

Calibrating the microscopic contact parameters is crucial when using DEM to model a material. By carefully calibrating these microscopic parameters, we can ensure that the DEM model accurately reflects the material's mechanical behavior at the micro and macro scales.

3.3 Calibration framework and results

Calibrating the microscopic parameters of the PB model is crucial for accurate GB-DEM modeling. Qu et al. (2020, 2022, 2019) proposed efficient parameter calibration methods that provide guidance for the calibration strategy and thinking of PBs. These parameters, which determine the macroscopic mechanical properties of the simulation specimen, are numerous and require a carefully designed calibration framework. To this end, we present a comprehensive calibration framework for multiscale contacts that encompasses grain and boundary scales as illustrated in Figure 11.

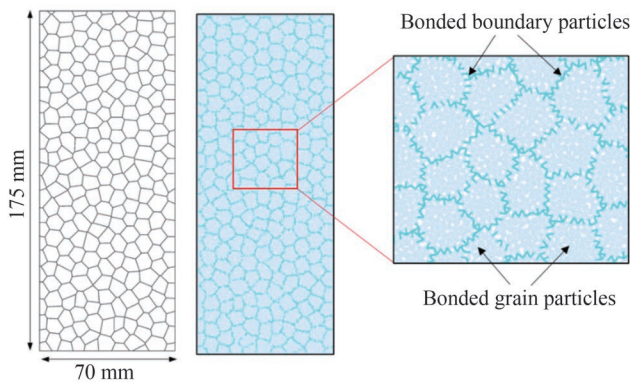


Figure 11 GB-DEM specimen (175 mm × 70 mm) in this study. (The black mesh represents the Voronoi grain mesh; the blue dashes represent the grain boundary contacts.)

The calibration framework for GB-DEM is based on the physical properties of ice, such as strength properties (e.g., UCS, confined compressive strength, and tensile strength) and elastic properties. A detailed discussion of the calibration work can be found in the reference provided (Sun et al., 2023), and the suggested microscopic parameters are sum-

marized in Table 3. By using these calibrated microscopic parameters in the GB-DEM model, we can accurately simulate the brittle mechanical behavior of ice and other fracture characteristics across a wide range of scales and loading conditions.

The calibration procedure follows a two-stage validated methodology (Sun et al., 2023; Peng et al., 2018b; Lan et al., 2010) as shown in Figure 12. First, TG parameters, including elastic modulus, UCS, and tensile strength, are calibrated using single-crystal ice experimental data (Carter, 1971). IG micromechanical parameters (elastic modulus, UCS, and tensile strength) are then determined using polycrystalline ice experimental data. This two-step approach systematically validates the model's capability to replicate intra- and intergrain mechanical responses, ensuring multi-scale consistency between micromechanical interactions and macroscopic ice behavior.

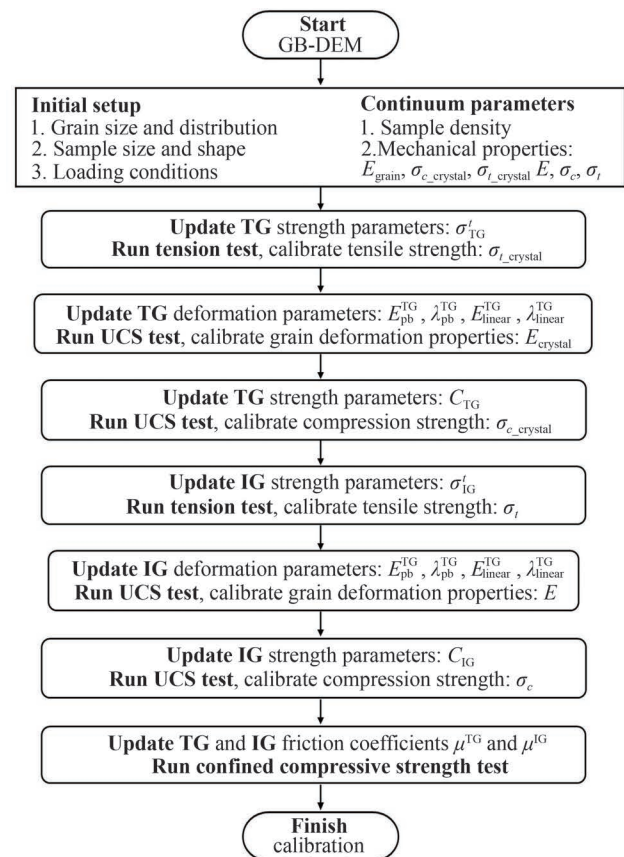


Figure 12 Calibration framework

According to the target values in Table 1, the initial values of all the parallel key mesoscopic parameters in contact within the model were set to the tensile strength and UCS of the single-crystal ice. Tensile strength calibration of single-crystal ice was then carried out. The calibration rule of the tensile strength in the discrete element was also confirmed. The tensile strength of the material is only affected

by the tensile strength of the PBs. During this process, the tensile strength of the PBs was calibrated. Next, the tensile strength of the TG PBs remains unchanged, and the tangential bonding strength was calibrated. During this process, the tangential bonding strength of the TG PBs was also calibrated. For the calibration of IG PBs, their tensile strength was first calibrated according to the tensile strength of polycrystalline ice, which was determined from the tensile strength of PBs. Next, the tangential bonding strength of IG was used to calibrate the UCS of polycrystalline ice. Once determined, the value was compared with existing data to verify the accuracy of the calibration framework.

Table 1 Calibration results (data from Sun et al. (2023))

Macroscopic properties	Physics properties	Modeling results	Error (%)
E_{crystal} (GPa)	11.0	11.1	0.91
$\sigma_{c_crystal}$ (MPa)	9.00	9.05	0.55
$\sigma_{t_crystal}$ (MPa)	2.30	2.28	0.87
E (GPa)	9.33	9.31	0.22
UCS σ_c (MPa)	5.20	5.38	3.40
TS σ_t (MPa)	0.75	0.72	4.00
$\sigma_{1@0.5 \text{ MPa}}$ (MPa)	7.80	7.52	3.50
$\sigma_{1@1.2 \text{ MPa}}$ (MPa)	10.10	9.68	4.75
$\sigma_{1@2.0 \text{ MPa}}$ (MPa)	12.15	11.98	0.14
$\sigma_{1@3.0 \text{ MPa}}$ (MPa)	15.20	15.12	0.05
$\sigma_{1@4.0 \text{ MPa}}$ (MPa)	19.12	18.00	5.83

After the microscopic parameters of single-crystal ice were determined, the mechanical properties of polycrystalline ice were then matched. The errors calculated by comparing the calibrated results and laboratory tests are shown in equation (16) and listed in Table 1. Table 2 summarizes all the calibrated particle parameters referring to the calibrating procedure.

$$\text{error} = \frac{|\text{target} - \text{simulation}|}{\text{target}} \times 100\% \quad (16)$$

The numerical calibration results of the GB-DEM model under the strain rate $4 \times 10^{-3}/\text{s}$ are shown in Figure 13, where (a) represents tension simulation, (b) represents uniaxial compressive simulation, and (c) represents confined pressure simulation. The fracture characteristics of polycrystalline ice were then investigated using a GBM model, which incorporates fine-tuned microscale parameters to simulate the behavior. As shown in Figure 13, our final validation revealed that the discrepancies between experimental and numerical results are 6%, 14%, and 13% under low (d), medium (e), and high strain rates (f), respectively.

Table 2 Calibrated results of microscopic parameters

Micro-parameters	Symbol	Value
Micro-properties of particles		
Minimum particle radius	$R_{\min}$ (m)	4.2×10^{-4}
Particle size ratio	$R_{\max}/R_{\min}$	1.5
Particle density	ρ (kg/m^3)	920
Damp		0.7
Micro-properties of TG contacts		
Parallel bond modulus	$E_{\text{pb}}^{\text{TG}}$ (GPa)	6.6
Parallel bond stiffness ratio	$\lambda_{\text{pb}}^{\text{TG}} \left(\frac{\bar{k}_n^{\text{TG}}}{\bar{k}_s^{\text{TG}}} \right)$	2
Parallel bond tensile strength	σ_{TG}^t (MPa)	3.5
Parallel bond cohesion	c_{TG} (MPa)	3.5
Particle contact modulus	$E_{\text{linear}}^{\text{TG}}$ (GPa)	6.6
Particle normal to shear stiffness ratio	$\lambda_{\text{linear}}^{\text{TG}} \left(\frac{k_n^{\text{IG}}}{k_s^{\text{IG}}} \right)$	2
Particle friction coefficient	μ^{TG}	0.85
Micro-properties of IG contacts		
Parallel bond modulus	$E_{\text{pb}}^{\text{IG}}$ (GPa)	1.6
Parallel bond stiffness ratio	$\lambda_{\text{pb}}^{\text{IG}} \left(\frac{\bar{k}_n^{\text{IG}}}{\bar{k}_s^{\text{IG}}} \right)$	2
Parallel bond tensile strength	σ_{IG}^t (MPa)	0.9
Parallel bond cohesion	c_{IG} (MPa)	1.6
Particle contact modulus	$E_{\text{linear}}^{\text{IG}}$ (GPa)	1.6
Particle normal to shear stiffness ratio	$\lambda_{\text{linear}}^{\text{IG}} \left(\frac{k_n^{\text{IG}}}{k_s^{\text{IG}}} \right)$	2
Particle friction coefficient	μ^{IG}	0.13
Loading wall-particle contacts		
Friction coefficient	μ^{pw}	0.9

We processed the fragments collected during the experiment into thin slices and observed the TG and IG microscopic cracks that occurred during the experiment. We also captured the TG and IG formed by the coalescence of the corresponding microscopic cracks during the simulation, as shown in Figure 13(g).

4 Simulation results

In this section, the rate-dependent properties of polycrystalline ice were studied through experiments and by using the grain-based numerical model of polycrystalline ice. In accordance with that observed during the experiment, the fracture process was reproduced through numerical simulation, and the rate-dependent effect of polycrystalline ice was analyzed from the microscopic fracture, crack propagation, fragmentation characteristics, and rate-dependent relationship of UCS.

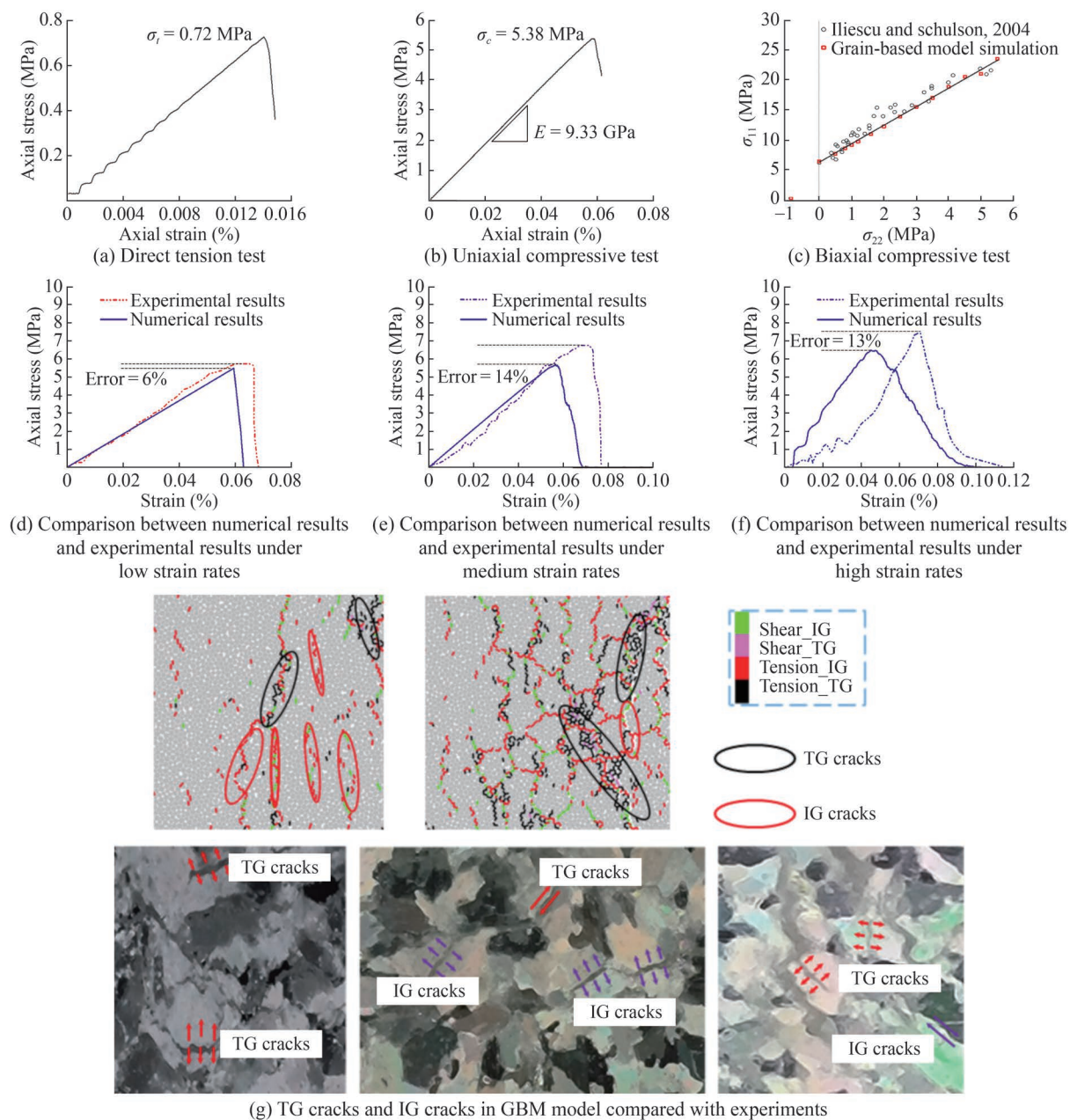


Figure 13 Numerical verification results of polycrystalline ice

4.1 Fracture process

Under compressive loading, the specimens exhibit brittle failure behavior. Five distinct stages were identified to elucidate the brittle failure mechanisms of polycrystalline ice, as shown in Figures 14 and 15. Figure 14 illustrates the stress-strain curve coupled with microscopic crack evolution under a strain rate of $2 \times 10^{-1}/s$, demonstrating the compressive response. The compressive stress initially increases linearly with strain and peaks at 5.52 MPa at a strain of 0.073% (corrected decimal placement for consistency). The stress-strain relationship was further divided into five critical stages (labeled A–E in Figure 15), each corresponding

to a specific fracture process characteristic. These stages reflect progressive crack nucleation, propagation, and eventual macroscopic failure.

Figure 14(b) displays the normalized evolution curve of microscopic crack quantities, where the normalized crack ratio was defined as the ratio of crack type counts to the corresponding IG and TG contact counts. A comparison of the crack evolution patterns in Figures 14(a) and 14(b) reveals that although TG cracks dominate numerically in Figure 14(a), the normalized damage degree of IG contacts remains the predominant factor throughout the specimen failure process.

The fracture evolution progresses through four distinct

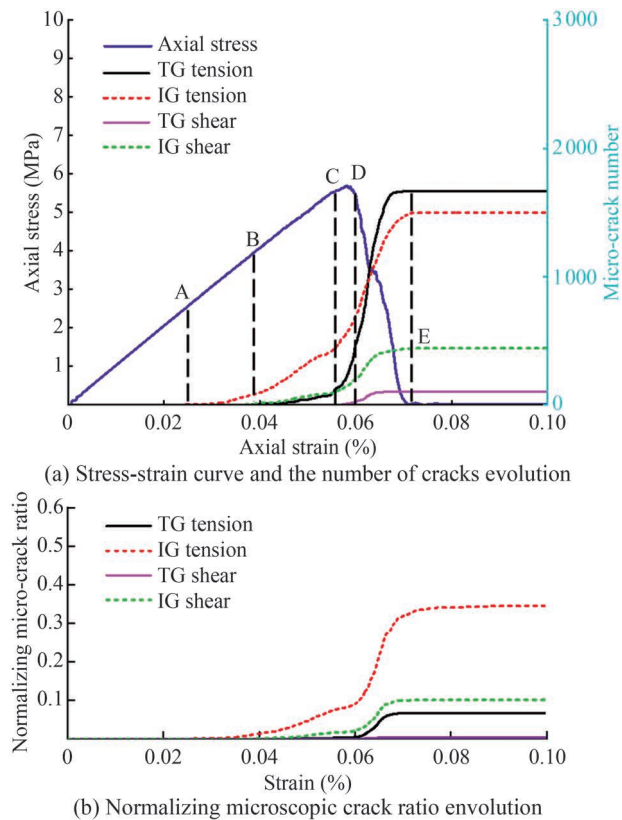


Figure 14 Stress-strain curve and evolution of different types of microcracks under the strain rate at $2 \times 10^{-1}/s$

stages marked by characteristic crack patterns. Stage A initiates microscopic crack formation, corresponding to the initial ascent of the crack quantity curve, with sporadic IG cracks showing limited spatial distribution. During the transition to Stage B, IG shear cracks emerge systematically and initial microcracks coalesce and partially propagate, resulting in broader crack distribution compared with that

in Stage A. Stage C demonstrates advanced fracture mechanisms where TG cracks concurrently penetrate crystal structures and pervasive IG crack networks, attributed to the continuous microcrack propagation that forms high-density fracture zones preceding macroscopic failure. In Stage D, the peak axial stress exhibits an abrupt curve decline, followed by accelerated crack growth rates (40%–60% higher than previous stages), accompanied by extensive plastic deformation and structural disintegration, culminating in complete specimen failure.

As shown in Figure 15, the initial random distribution of microcracks evolves into concentrated fractures with the increase in strain, with the cracks coalescing and transitioning from stage B to stage C. In the subsequent stage, a concentrated long wedge crack appears as shown in Stage C, followed by a crack throughout the entire sample as illustrated in Stage D. When the stress peaks, the sample fails under irregular fractures. The dominant cracks initiated in the middle of the specimen are formed by the grain boundary tension, with an average orientation angle range of $60^\circ \leq \theta \leq 120^\circ$. As the loading progresses, the number of cracks inside the specimen increases. IG cracks remain the main type of microcracks in the early stages of loading, and their angular distribution is mainly concentrated in the range of $60^\circ \leq \theta \leq 120^\circ$. Shear cracks also appear as shown in Figure 15(c) and primarily occur at grain boundaries, with their angular distribution falling in between.

4.2 Effect of strain rate on energy transition

In the proposed numerical model, the breaking of bonds and ice fragmentation are treated as irreversible phenomena involving continuous energy conversion and dissipation. Hence, the dissipated energy, which comprises frictional losses E_f and kinetic energy E_k , can be directly eval-

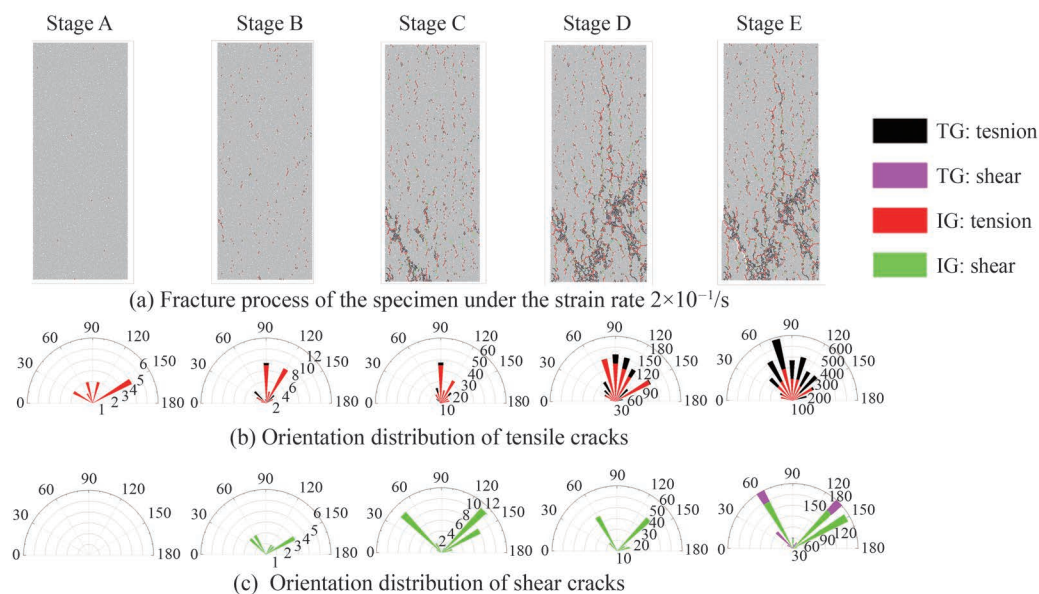


Figure 15 Propagation and orientation distribution of microscopic cracks

uated using the GB-DEM numerical approach.

$$E_f = \int \sum_{i=1}^{N_c} (\langle F_i^s \rangle \Delta u_i^{\text{slip}}) dt \quad (17)$$

$$E_k = \frac{1}{2} \sum_{i=1}^{N_p} (m_i v_i^2 + \bar{I}_i \omega_i^2) \quad (18)$$

where N_c and N_p represent the number of the linear contact between particles and particles in the specimen, respectively. $\langle F_i^s \rangle$ is the averaged sliding force, and Δu_i^{slip} is the current slip increment. M_i , v_i , w_i , and $\bar{I}_i$ are the mass, velocity components, rotation, and moment of inertia of the particle, respectively. As shown in Figure 16, the aforementioned energies, including kinetic energy, frictional energy, and dissipated energy, are rate-dependent.

Kinetic energy is the byproduct of the translational motion of particles after the PBs break under external loading conditions. As the strain rate varied, the kinetic energy increased from 0.3 to 17 J. Moreover, the variation of strain rate leads to an increase in frictional energy from 2 to 23 J. Figure 16 shows that under axial compressive loading, the contribution of kinetic energy to the dissipated energy increases with the strain rate due to the generation of freely moving fragments of the specimen at high strain rates. This phenomenon results in an increase in the proportion of kinetic energy to the dissipated energy from 1% to 43% at the strain interval from 4×10^{-3} /s to 10/s. The frictional energy manifests as the relative sliding between the contact points of particles. During this process, frictional force exists between particles, causing the generation of frictional energy.

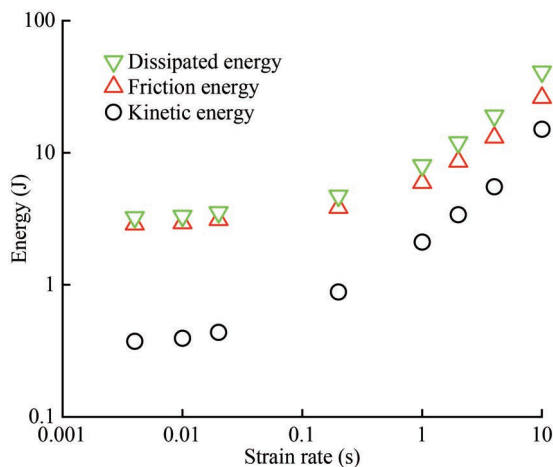
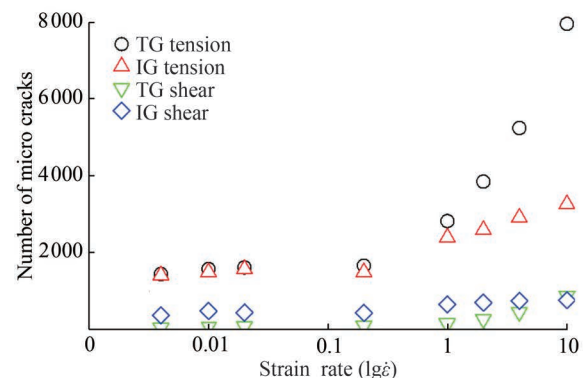


Figure 16 Energy transition in unconfined compressive strength tests at different strain rates

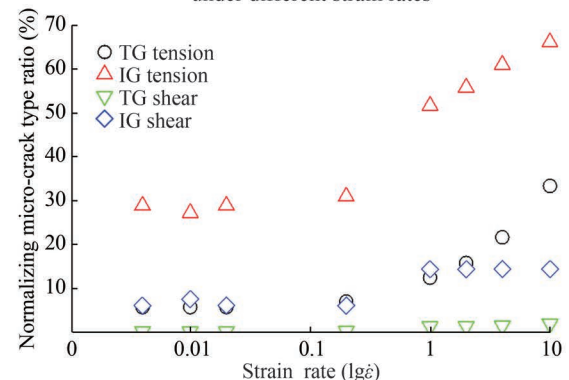
4.3 Effect of strain rate on microscopic fracture

The number of fractures in the final state of the specimen varies with the strain rate, as shown in Figure 17. In general, the evolution and law of crack number differ with the strain rate. From 4×10^{-3} /s to 10/s, almost no signifi-

cant change is observed in the number of microscopic cracks. When the strain rate exceeds 2×10^{-1} /s, the number of tension cracks increases dramatically, but the growth of shear microscopic cracks is not pronounced. When the strain rate is under 2×10^{-1} /s, the ratio of tension microscopic cracks is approximately 85%, and the IG tension crack ratio is almost equal to the TG tension crack. This value increases to 90% when the strain rate increases to 10/s. The ratio of TG tension cracks also increases from 45% to 64% with the increasing strain rates. At the same time, the ratio of IG tension cracks decreases from 43% to 26%. The proportion of shear cracks remains low. With the increase in strain rate, the proportion of IG shear cracks decreases while that TG shear cracks increases. Furthermore, the ratio of TG cracks becomes higher than that of IG cracks, revealing that the microfracture transits from IG to TG.



(a) Difference of the number of microscopic cracks under different strain rates



(b) Difference of the number of normalizing microscopic cracks under different strain rates

Figure 17 Microscopic crack number change and fracture type ratio at different strain rates

The changes in the number of cracks and the evolution of crack types are mainly reflected in the failure and breakage of the specimen. Figure 18(a) shows the distribution of microscopic cracks in several samples under different strain rates. With the increase in strain rate, the distribution of microscopic cracks in the samples becomes dense. In the transformation from low rate to high rate, the local density

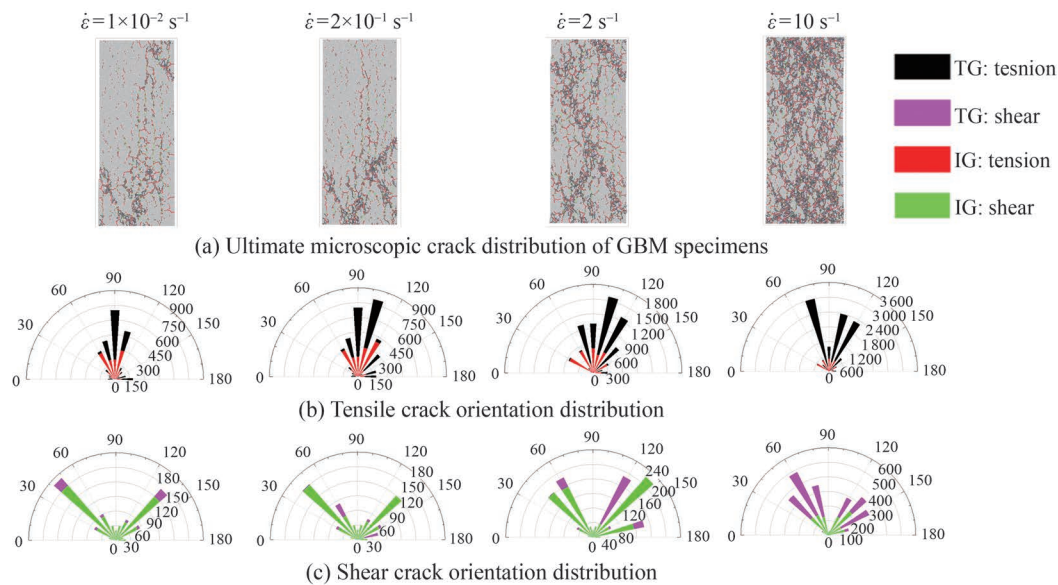


Figure 18 Crack orientation distribution at four different strain rates

changes for almost every sample filled with microscopic cracks. With the increase in strain rate from $1 \times 10^{-2}/\text{s}$ to $10/\text{s}$, the cracks leading to the failure of the sample change from the initial split crack (such as specimens under $1 \times 10^{-2}/\text{s}$) that runs through the whole sample to the short fracture crack (such as specimens under $10/\text{s}$) inside the sample.

Although the increase in strain rate leads to an increase in the number of microcracks, the angular distribution and number of microcracks also change. Figures 18(b) and 18(c) show that although the number of tensile microcracks is concentrated at $60^\circ \leq \theta \leq 120^\circ$, the maximum number of cracks changes from the initial rate of 90° to the final rate of 68° . This finding indicates that some of the main declination angles of the final crack failure are altered. With the increase in strain rate, the main crack orientation of the sample begins to move away from the loading direction.

4.4 Effect of strain rate on fragment characterization

The fragment of the specimen is determined by the microscopic fracture process and influences the energy dissipation under uniaxial compressive loading to some extent. In the modeling, the fragment sequence was mobilized as all the boundary bonds of the assembly are ruptured, and the clustered particles become an independent island. Figure 19 presents the ultimate fragment states at eight different strain rates. Different colors were used to differentiate the fragments. With the change in strain rate, the final failure mode of the sample changes from the specimen without evident fragments to the final pulverizing mode. The final fragmentation modes of GBMs are in great agreement with those observed in the laboratory tests shown in Figure 20.

Figure 20 shows the true fracture mode of polycrystalline ice during the test, and the corresponding fracture failure occurs in the sample under axial compression load.

Under low strain rates (Figure 20(a)), the damaged sample can still be completely assembled into a complete sample. With the increase in strain rate, the fragmentation level of the sample increases (Figure 20(b)) and the final fragments become difficult to piece together into a complete sample.

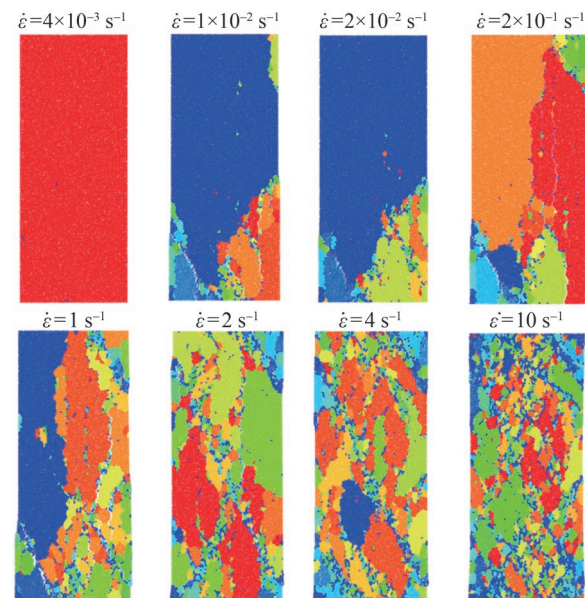


Figure 19 Ultimate fragment states of the specimen at eight strain rates: different colors are used to differentiate the fragments

By combining the numerical simulation and test, the probability distribution of debris area of polycrystalline ice under different strain rates was calculated as shown in Figure 21. Figure 21(a) displays the probability distribution of the fragment area of the numerically simulated sample under different strain rates. The fragment area at 50% was calculated

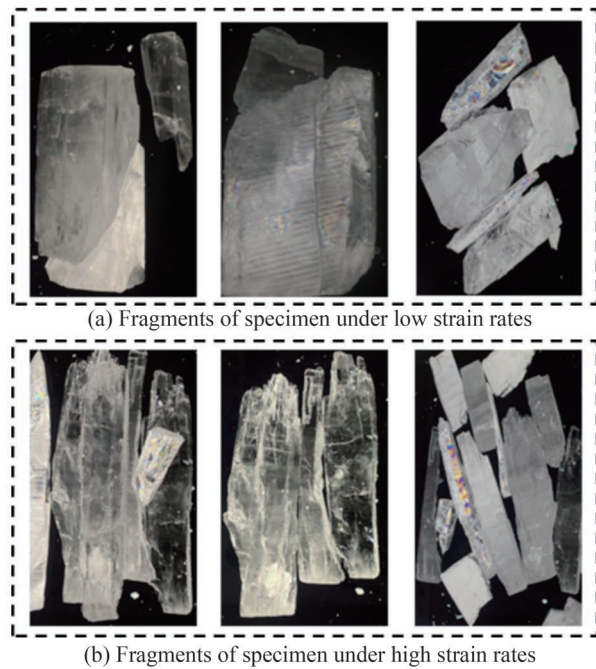


Figure 20 Microscopic fracture distribution of ultimate specimens at different strain rates

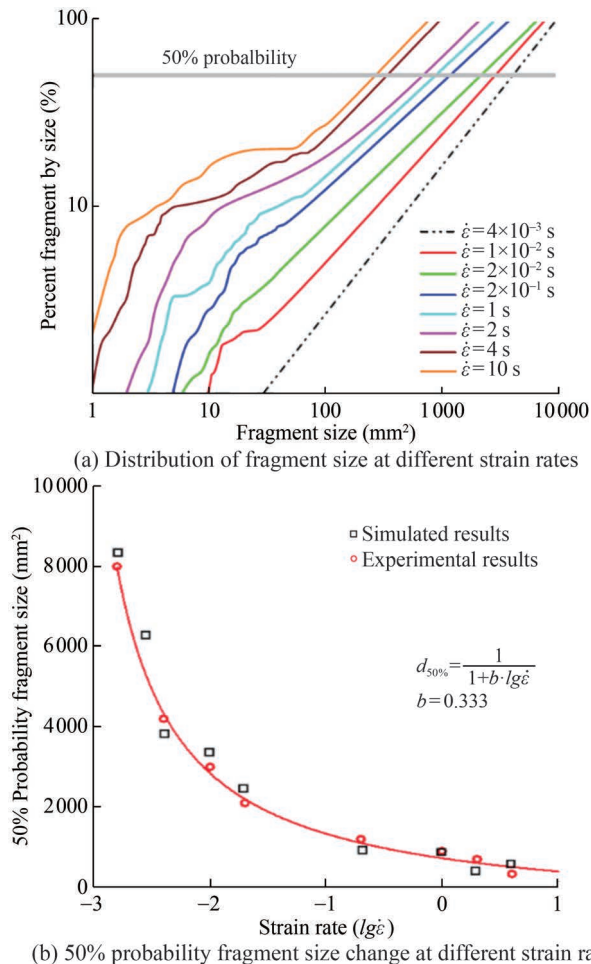


Figure 21 Fragment distribution of ultimate specimens

from the probability distribution curve. In this work, the median particle size ($d_{50\%}$) was used as an indicator to measure the fragmentation of polycrystalline ice samples. It represents the extent of damage to the samples under different strain rates: the smaller the $d_{50\%}$ value, the higher the fragmentation degree of the samples. Figure 21(b) shows that $d_{50\%}$ is significantly negatively correlated with the strain rate, that is, the larger the strain rate, the smaller the $d_{50\%}$ value.

Figure 22 shows the hand-drawn diagram of the failure of the polycrystalline ice sample. At low strain rates, the fracture failure of the sample is single, a few branch cracks appear near the main crack, and the fragments are also large. With a further increase in strain rate, the fragment area decreases, the main cracks are no longer single, and the branch cracks begin to increase. When the strain rate reaches 10/s, the sample is violently crushed, and the cracks and branch cracks intermingle.

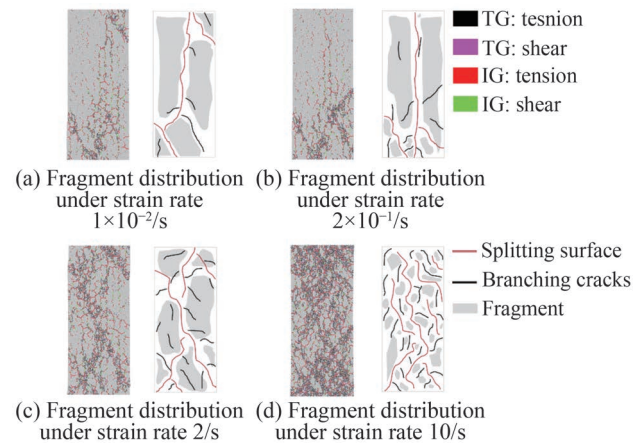


Figure 22 Hand drawing for microscopic fracture distribution of ultimate specimens at four different strain rates

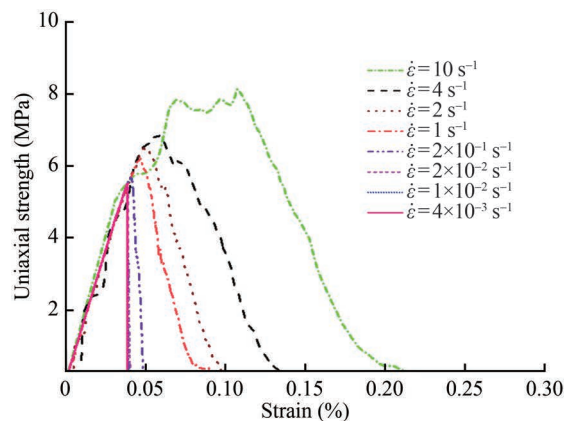
4.5 Effect of strain rate on unconfined compressive strength

After understanding the brittle failure and microfracture of polycrystalline ice from the crystal scale, we discuss the rate-dependent effect of polycrystalline ice from the macroscopic mechanical response. The relationship between UCS and strain rate was determined from the UCS of polycrystalline ice. Obtaining a rate-dependent model for the UCS of polycrystalline ice is a significant issue. In this section, the experimental results and numerical simulations were combined to develop a rate-dependent model tailored for the UCS of polycrystalline ice. On the basis of the UCS values at low and different strain rates, a UCS rate correlation factor RDF was proposed:

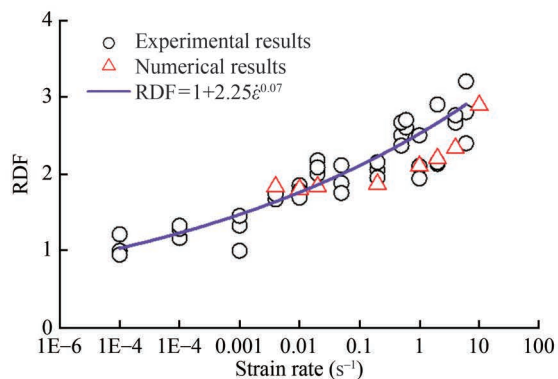
$$\text{RDF} = \frac{\sigma_c}{\sigma_{\text{nominal}}} \quad (19)$$

where σ_c is the UCS under high strain rates, σ_{nominal} is UCS value when the strain rate is $4 \times 10^{-3}/\text{s}$ from the labo-

ratory test in Section 2. Finally, the stress-strain curve of the numerical test was statistically analyzed, and the results shown in Figure 23(a) reflect the correlation of the stress response rate of the numerical sample under different strain rates. In the rate range below $2 \times 10^{-1}/s$, the stress-strain response of the polycrystalline ice sample shows minimal difference. When the strain rate exceeds this value, the stress-strain curve changes greatly. The initial stage is linear elasticity. However, with the increase in strain rate, the stress-strain curve at the initial stage is no longer stable due to the uneven distribution of stress inside the sample. With the increase in strain rate, the peak UCS is positively correlated with the strain rate.



(a) Stress-strain curves of numerical specimens under different strain rates



(b) Rate-dependent factor fit curve combined with numerical and experimental results

Figure 23 Uniaxial compressive strength curves under different strain rates

As shown in Figure 23(b), the UCS rate dependence factor obtained from the polycrystalline ice sample test was fitted and found to be consistent for the numerical and experimental tests. Finally, the rate-dependent model based on experimental and numerical methods is shown in equation (20):

$$\text{RDF} = 1 + 2.25\dot{\epsilon}^{0.07} \quad (20)$$

This rate-dependent model reflects the mechanical

response of polycrystalline ice under different loading rates in terms of UCS. It should be suitable for scenarios where the strain rate is less than 10/s.

5 Discussion

In this study, combined numerical and experimental methods were adopted to explore the failure characteristics of polycrystalline ice under different strain rates to further understand the uniaxial compressive strain rack-related characteristics of polycrystalline ice. The test results are reasonable as shown in Figure 5, proving that polycrystalline ice has a strain rate effect, whether from the stress-strain curve or from the failure mode of the sample. The laboratory test of UCS is also within a reasonable range of magnitude when compared with other existing results. Our model is based on the discussion of the rate dependence of polycrystalline ice, and the strain rate range studied is between $4 \times 10^{-3}/s$ and 10/s.

For the numerical model, we adopted the DEM. The established numerical model based on the real grain structure of S2 columnar ice is the basic work in the early stage. To establish the numerical model of ice, Voronoi also applied other methods (Lu et al., 2020; Li et al., 2023; Gribanov et al., 2018a; Gribanov et al., 2018b; Sun et al., 2023). The key point of the DEM is to select the appropriate bond contact model to describe the failure behavior of the material. The damage and microscopic fractures occurring within the material are manifested in the DEM as the damage of PBs. For the mechanical modeling of ice, the reproduction and reasonable description of the destructive behavior is an important link. The selected PB model can describe the behavior of brittle failure inside ice, while the GB-DEM polycrystalline ice model can reflect the initiation, propagation, and coalescence of microscopic cracks.

A discrete element calibration framework capable of calibrating multiscale mechanical parameters was successfully implemented, obtaining discrete element mesoscopic parameter groups that can meet the mechanical properties of single-crystal and polycrystalline ice. On the premise of the good comparison between the experimental and numerical results, further research on the failure characteristics of polycrystalline ice was carried out using numerical experiments. With the change in strain rate, the difference in crack propagation within the GB-DEM model leads to the transformation of the final failure mode of the specimen from splitting to fragmentation. In addition, the number of microscopic cracks inside polycrystalline ice increases, aggravating particle movement such as friction and dissipation. Under the increase in strain rate, the kinetic energy of the sample also increases, and the movement speed of the particles is controlled by the strain rate.

6 Conclusion

6.1 Main conclusion of this study

The main results of this research are as follows:

1) The specimen was obtained from the Songhua River during winter, and the grain structure of columnar ice was observed. Uniaxial compression tests were conducted at a laboratory scale to investigate the stress-strain behavior and failure modes of polycrystalline ice under different strain rates. Results showed that the UCS and failure modes exhibited a significant rate-dependent effect. The UCS showed an initial increase and a subsequent decrease with the increasing strain rate. Moreover, the failure mode transitioned from cleavage fracture to comminution as the strain rate increased.

2) This study presented a numerical model for polycrystalline ice based on the geometric topology of polycrystalline ice observed in experiments. A 2D model for columnar ice in the horizontal direction was established by defining two contact groups in the discrete element. On the basis of the mechanical properties of polycrystalline ice, the microscopic parameters in the DEM numerical model were numerically calibrated and found to be consistent with the experimental results under a nominal strain rate. Therefore, the numerical model used in this study is suitable for investigating the fracture characteristics of ice under compressive loading at different strain rates.

3) This study investigated the strain rate-dependent behaviors of ice specimens under axial compressive loading through a combination of numerical simulations and laboratory experiments. The findings revealed that the axial compressive strength, internal microcrack propagation, internal dissipated energy conversion, and fracture fragmentation characteristics of the ice specimens all exhibited significant strain rate-dependent effects. The strain rate of 2×10^{-1} /s was a rate-dependent transition point, after which the rate-dependent effect of polycrystalline ice became evident and the damage became severe. These findings are crucial for an improved understanding of the mechanical response of ice and its engineering applications. Using the proposed rate-dependent model, we can perform ice load calculations at the engineering scale.

6.2 Future developments of continuity-related work

1) This study combines experimental and discrete element numerical methods to investigate the rate-dependent behavior of polycrystalline ice. A mechanical model for polycrystalline ice is established at the crystal scale, and the microstructural parameters of the discrete element numerical model are calibrated using multiple scales. This approach allows for a comprehensive understanding of the brittle failure mechanisms in polycrystalline ice. However, given the inherent complexity of polycrystalline ice as a material,

its mechanical properties and structural behavior are sensitive to external loading conditions and structural disparities. Addressing these challenges will be the focus of future research endeavors.

2) This work studies the polycrystalline ice fracture mechanism using GBM to explain the special phenomena observed in the experimental results from multiple perspectives. However, in practical applications, the fracture problem of grain boundaries in polycrystalline ice is challenging due to its unique geometric morphology and mechanical properties. Further research is warranted on modeling grain boundaries and their fracture problems to accurately describe the mechanical properties of polycrystalline ice in numerical models.

3) This study develops a numerical model at the laboratory scale. However, our ultimate goal is to directly apply this model's observed phenomena and conclusions to the research and development of equipment in polar regions. Existing upscaling methods provide a practical approach by obtaining a representative volume element at a low scale. We can then investigate the mechanical behavior of this representative volume element and apply the derived mechanical laws to engineering-scale applications using appropriate methods. This concept has already been successfully applied in upper scaling calculations for other brittle materials. Considering the similarities of ice with other brittle materials, we believe that a multiscale computational framework applicable to the field of polar regions will be proposed in the future.

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Competing interest The authors have no competing interests to declare that are relevant to the content of this article.

References

- Carney K, Benson D, DuBois D, Lee R (2006) A phenomenological high strain rate model with failure for ice. *International Journal of Solids and Structures* 43(25): 7820–7839. <https://doi.org/10.1016/j.ijsolstr.2006.04.005>
- Carter D (1971) Lois et mécanismes de l'apparente fracture fragile de la glace de rivière et du lac
- Cole D, Shapiro L, Weeks W, Byers C, Dempsey J, Adamson R, Petrenko V, Gluschenkov V (1995) Overview of Recent Program on Mechanical Properties of Sea Ice. *Journal of Cold Regions Engineering* 9(4): 219–234. [https://doi.org/10.1061/\(ASCE\)0887-381X\(1995\)9:4\(219\)](https://doi.org/10.1061/(ASCE)0887-381X(1995)9:4(219))
- Cundall P (1971) A computer model for simulating progressive, large-scale movement in blocky rock system. *Proceedings of the International Symposium on Rock Mechanics*

- Cundall P, Strack O (1979) A discrete numerical model for granular assemblies. *Geotechnique* 29(1): 47-65. <https://doi.org/10.1680/geot.1980.30.3.331>
- Di SC, Xue YZ, Wang Q, Bai XL (2017) Discrete element simulation of ice loads on narrow conical structures. *Ocean Engineering* 146: 282-297. <https://doi.org/10.1016/j.oceaneng.2017.09.033>
- Gao FQ, Stead D, Elmo D (2016) Numerical simulation of microstructure of brittle rock using a grain-breakable distinct element grain-based model. *Computers and Geotechnics* 78: 203-217. <https://doi.org/10.1016/j.compgeo.2016.05.019>
- Gribanov I, Taylor R, Sarracino R (2018a) Cohesive zone micromechanical model for compressive and tensile failure of polycrystalline ice. *Engineering Fracture Mechanics* 196: 142-156. <https://doi.org/10.1016/j.engfracmech.2018.04.023>
- Gribanov I, Taylor R, Sarracino R (2018b) Application of cohesive zone model to the fracture process of freshwater polycrystalline ice under flexural loading. in *IOP Conference Series: Earth and Environmental Science*. IOP Publishing. <https://doi.org/10.1088/1755-1315/193/1/012013>
- Hawkes I, Mellor M (1972) Deformation and fracture of ice under uniaxial stress. *Journal of Glaciology* 11(61): 103-131. <https://doi.org/10.3189/s002214300002253x>
- Ji SY, Chen XD, Wang AL (2020) Influence of the loading direction on the uniaxial compressive strength of sea ice based on field measurements. *Annals of Glaciology* 61(82): 86-96. <https://doi.org/10.1017/aog.2020.14>
- Jones S (1997) High Strain-Rate Compression Tests on Ice. *The Journal of Physical Chemistry B* 101(32): 6099-6101. <https://doi.org/10.1021/jp963162j>
- Kim H, Keune J (2007) Compressive strength of ice at impact strain rates. *Journal of Materials Science* 42(8): 2802-2806. <https://doi.org/10.1007/s10853-006-1376-x>
- Lan HX, Martin C, Hu B (2010) Effect of heterogeneity of brittle rock on micromechanical extensile behavior during compression loading. *Journal of Geophysical Research: Solid Earth* 115(B1). <https://doi.org/10.1029/2009JB006496>
- Li JB, Wang CY, Wang Q, Zhang YH, Jing CY, Han DF (2023) Peridynamic modeling of polycrystalline S2 ice and its applications. *Engineering Fracture Mechanics* 277: 108941. <https://doi.org/10.1016/j.engfracmech.2022.108941>
- Li XF, Li HB, Zhao J (2021) Transgranular fracturing of crystalline rocks and its influence on rock strengths: Insights from a grain-scale continuum-discontinuum approach. *Computer Methods in Applied Mechanics and Engineering* 373: 113462. <https://doi.org/10.1016/j.cma.2020.113462>
- Li XF, Li X, Li HB, Zhang QB, Zhao J (2018) Dynamic tensile behaviours of heterogeneous rocks: the grain scale fracturing characteristics on strength and fragmentation. *International Journal of Impact Engineering* 118: 98-118. <https://doi.org/10.1016/j.ijimpeng.2018.04.006>
- Li ZJ, Zhang LM, Lu P, Leppäranta M, Li GW (2011) Experimental study on the effect of porosity on the uniaxial compressive strength of sea ice in Bohai Sea. *Science China Technological Sciences* 54(9): 2429-2436. <https://doi.org/10.1007/s11431-011-4482-1>
- Liu RW, Xue YZ, Li SF (2023) A general finite deformation hypoelastic-plasticity non-ordinary state-based peridynamics model and its applications. *Engineering with Computers* 40: 1-20. <https://doi.org/10.1007/s00366-023-01792-0>
- Liu RW, Xue YZ, Han DF, Ni BY (2021) Studies on model-scale ice using micro-potential-based peridynamics. *Ocean Engineering* 221: 108504. <https://doi.org/10.1016/j.oceaneng.2020.108504>
- Lu WJ, Hans-Martin Heyn, Raed Lubbad, Sveinung Løset (2018) A large scale simulation of floe-ice fractures and validation against full-scale scenario. *International Journal of Naval Architecture and Ocean Engineering* 10(3): 393-402. <https://doi.org/10.1016/j.ijnaoe.2018.02.006>
- Lu W, Li MY, Vazic B, Oterkus S, Oterkus E, Wang Q (2020) Peridynamic modelling of fracture in polycrystalline ice. *Journal of Mechanics* 36(2): 223-234. <https://doi.org/10.1017/jmech.2019.61>
- Ni BY, Han DF, Di SC, Xue YZ (2020) On the development of ice-water-structure interaction. *Journal of Hydrodynamics* 32(4): 629-652. <https://doi.org/10.1007/s42241-020-0047-8>
- Peng J, Wong L, Teh C (2017) Influence of grain size heterogeneity on strength and microcracking behavior of crystalline rocks. *Journal of Geophysical Research: Solid Earth* 122(2): 1054-1073. <https://doi.org/10.1002/2016JB013469>
- Peng J, Wong L, Teh C (2018a) A re-examination of slenderness ratio effect on rock strength: Insights from DEM grain-based modelling. *Engineering Geology* 246: 245-254. <https://doi.org/10.1016/j.enggeo.2018.10.003>
- Peng J, Wong L, Teh C, Li ZH (2018b) Modeling micro-cracking behavior of Bukit Timah granite using grain-based model. *Rock mechanics and rock engineering* 51(1): 135-154. <https://doi.org/10.1007/s00603-017-1316-x>
- Prasanna M, Polojärvi A, Wei MD, Åström J (2022) Modeling ice block failure within drift ice and ice rubble. *Physical Review E* 105: 045001. <https://doi.org/10.1103/PhysRevE.105.045001>
- Qu TM, Feng YT, Wang M, Jiang SQ (2020) Calibration of parallel bond parameters in bonded particle models via physics-informed adaptive moment optimisation. *Powder Technology* 366: 527-536. <https://doi.org/10.1016/j.powtec.2020.02.077>
- Qu TM, Feng YT, Zhao JD (2022) A strain energy-based elastic parameter calibration method for lattice/bonded particle modelling of solid materials. *Powder Technology* 410: 117860. <https://doi.org/10.1016/j.powtec.2022.117860>
- Qu TM, Feng YT, Zhao TT, Wang M (2019) Calibration of linear contact stiffnesses in discrete element models using a hybrid analytical-computational framework. *Powder Technology* 356: 795-807. <https://doi.org/10.1016/j.powtec.2019.09.016>
- Schulson E, Gratz E (1999) The brittle compressive failure of orthotropic ice under triaxial loading. *Acta Materialia* 47(3): 745-755. [https://doi.org/10.1016/S1359-6454\(98\)00410-8](https://doi.org/10.1016/S1359-6454(98)00410-8)
- Schulson E, Lim P, Lee R (1984) A brittle to ductile transition in ice under tension. *Philosophical Magazine A* 49(3): 353-363. <https://doi.org/10.1080/01418618408233279>
- Schulson E (1997) The brittle failure of ice under compression. *The Journal of Physical Chemistry B* 101(32): 6254-6258. <https://doi.org/10.1021/jp9632192>
- Schulson E (2001) Brittle failure of ice. *Engineering fracture mechanics* 68(17-18): 1839-1887. [https://doi.org/10.1016/S0013-7944\(01\)00037-6](https://doi.org/10.1016/S0013-7944(01)00037-6)
- Schulson E (2009) Creep and fracture of ice. Cambridge university press. <https://doi.org/10.1017/CBO9780511581397>
- Schulson E, Gratz E (2009) The brittle compressive failure of orthotropic ice under triaxial loading. *Acta Materialia* 47(3): 745-755. [https://doi.org/10.1016/S1359-6454\(98\)00410-8](https://doi.org/10.1016/S1359-6454(98)00410-8)
- Schulson E (1990) The Brittle Compressive Fracture of ice. *Acta Metallurgica et Materialia* 38(10): 1963-1976. [https://doi.org/10.1016/0956-7151\(90\)90308-4](https://doi.org/10.1016/0956-7151(90)90308-4)
- Shazly M, Prakash V, Lerch B (2009) High strain-rate behavior of ice under uniaxial compression. *International Journal of Solids and Structures* 46(6): 1499-1515. <https://doi.org/10.1016/j.ijsolstr.2008.11.020>

- Shafrova S, Høyland K (2008) The freeze-bond strength in first-year ice ridges. Small-scale field and laboratory experiments. *Cold Regions Science and Technology* 54(1): 54-71. <https://doi.org/10.1016/j.coldregions.2007.11.005>
- Sun GS, Di SC, Feng YT, Xue YZ (2023) Modelling the fracture behaviour of polycrystalline columnar ice using the grain-based discrete element method. *Computational Particle Mechanics* 10: 1877-1894. <https://doi.org/10.1007/s40571-023-00595-w>
- Taylor R, Jordaan I (2015) Probabilistic fracture mechanics analysis of spalling during edge indentation in ice. *Engineering Fracture Mechanics* 134: 242-266. <https://doi.org/10.1016/j.engfracmech.2014.10.021>
- Timco G, Weeks W (2010) A review of the engineering properties of sea ice. *Cold regions science and technology* 60(2): 107-129. <https://doi.org/10.1016/j.coldregions.2009.10.003>
- Timco G, Frederking R (1986) Confined compression tests: outlining the failure envelope of columnar sea ice. *Cold Regions Science and Technology* 12(1): 13-28. [https://doi.org/10.1016/0165-232X\(86\)90016-9](https://doi.org/10.1016/0165-232X(86)90016-9)
- Yuan GY, Ni BY, Wu QG, Xue YZ, Han DF (2022) Ice breaking by a high-speed water jet impact. *Journal of Fluid Mechanics* 934: A1. <https://doi.org/10.1017/jfm.2021.999>
- Zhang LM, Li ZJ, Jia Q, Li GW, Huang WF (2011) Uniaxial Compressive Strengths of Artificial Freshwater Ice. *Advanced Materials Research* 243-249: 4634-4637. <https://doi.org/10.4028/www.scientific.net/AMR.243-249.4634>
- Zhang YH, Wang Q, Han DF, Xue YZ, Lu SC, Wang PG (2020) Dynamic splitting tensile behaviours of distilled-water and river-water ice using a modified SHPB setup. *International Journal of Impact Engineering* 145: 103686. <https://doi.org/10.1016/j.ijimpeng.2020.103686>
- Zhang YH, Wang Q, Han DF, Xue YZ, Qu J, Yao HQ (2021a) Experimental study of the quasi-static and dynamic fracture toughness of freshwater ice using notched semi-circular bend method. *Engineering Fracture Mechanics* 247: 107696. <https://doi.org/10.1016/j.engfracmech.2021.107696>
- Zhang YD, Li ZJ, Xiu YR, Li CJ, Zhang BS, Deng Y (2021b) Microstructural characteristics of frazil particles and the physical properties of frazil ice in the yellow river, China. *Crystals* 11(6): 617. <https://doi.org/10.3390/cryst11060617>