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Discrete Element Simulation of Sea Ice Flexural Strength

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The flexural strength of sea ice is a key parameter in determining the ice load on offshore structures. A series of field and indoor physical tests have been carried out and the relationship between the sea ice flexural strength and sea ice parameters, such as ice temperature, salinity and sample size, has been obtained. In this study the discrete element model (DEM) is adopted to calculate the sea ice flexural strength under different ice parameters. The ice samples are constructed with regular and random packing patterns of spherical elements, respectively. To analyze the influence of particle size effect on flexural strength, three different particle sizes are chosen in the DEM simulation. The simulated flexural strengths are quite close with different particle sizes for both of the regular and random packing. The influence of bonding strength between particles is also investigated by sensitivity analysis. Finally, the feasibility of DEM in sea ice flexural strength simulation is validated by physical measurements data.

1. Introduction

In the interaction between sea ice and slope offshore structures or ships, bending failure is a predominant failure mode. The flexural strength is an important parameter to determine the ice load. Moreover, the break-up, ride-up, rafting and ridge-building of sea ice under wave, wind and current actions, and the bearing capacity of sea ice covers are closely related to the flexural strength (Kovacs and Sodhi 1980; Masterson 2009). Therefore, it is important to study the flexural strength of sea ice and make clear the bending failure process in sea ice engineering.

Recently, some field tests and indoor tests were carried out to study the flexural strength of sea ice during bending failure process. The simple beam tests are conducted in situ or in the laboratory, and ice samples can be loaded at three or four equidistant points. As a complex crystal material, sea ice flexural strength is affected by many factors. Ice temperature and ice salinity have an obvious influence on the flexural strength (Zhang et al., 1993; Blanchet 1997). Timco and O'Brien (1994) summarized previous flexural strength tests and pointed out the flexural strength of sea ice has a negative exponential relationship to square root of brine volume. Some tests also show that sea ice flexural strength increases with increasing stress rate (Gagnon et al., 1995).

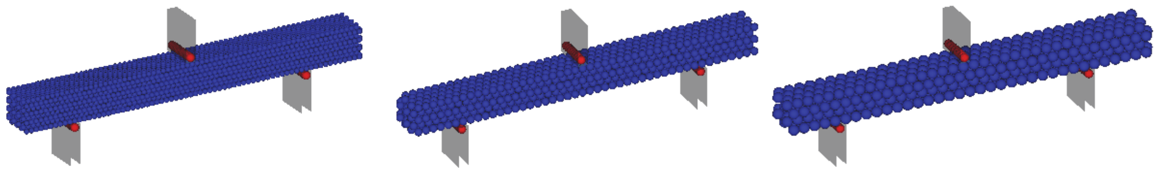
In this paper, we adopt the discrete element method (DEM) to simulate the ice flexural strength. Considering the influence of sea ice temperature and salinity, a spherical particle model with parallel bonding is adopted. Considering the granular and columnar structures of sea ice on micro scale, the sea ice samples of bending tests are constructed with regular and random packing, respectively. The simulated results are compared with the physical experiment data.

2. Microstructure of Sea Ice and Discrete Element Model

2.1 Particle Packing

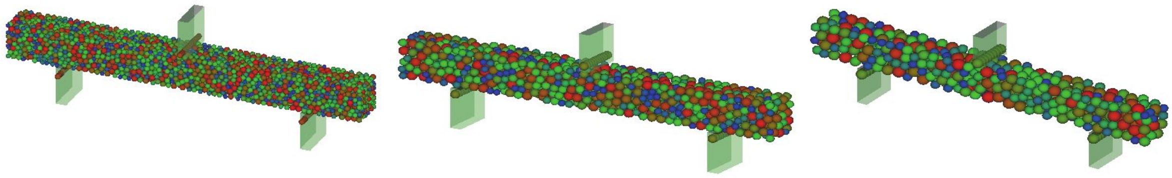
Generally, sea ice is a complex material that is composed of solid ice, brine and gas. On micro scale, the sea ice appears as different grain structures under different environmental conditions in its growing process. The most common grain structures include granular, columnar, and discontinuous columnar (Timco and Weeks, 2011). Here an important fact is that sea ice is isotropic with granular structures as well as is anisotropic with columnar structures. These differences are, in turn, reflected in variations in the mechanical properties of the ice. Therefore, the irregular packing of granular particles is adopted to model the sea ice mechanical properties with DEM properly. While if we try to model the columnar sea ice, the regular packing can be applied. Here, the sea ice samples are constructed with regular packing and irregular packing, respectively. With the different packing patterns, the flexural strengths of sea ice will be simulated with DEM in the next section.

Based on the microstructure of sea ice material, the sea ice sample is constructed with regular packing and random packing, respectively. The sea ice sample size is designed as 70 mm high, 70 mm wide and 700 mm long. Here, we set the particle diameters (D) as 10 mm, 15 mm and 20 mm to study the influence of particle size on the sea ice strength. For the regular packing pattern, the particle numbers are 4480, 1150, 560 for different particle sizes, respectively. The particles numbers are 4406, 1305 and 550 for irregular packing pattern. The sea ice sample constructed with different particle sizes are shown in Figs. 1~2.



(a) D=10 mm (b) D=15 mm (c) D=20 mm

Figure 1. Sea ice sample constructed with regular particle packing with different particle sizes.



(a) D=10 mm (b) D=15 mm (c) D=20 mm

Figure 2. Sea ice sample constructed via random particle packing with different particle sizes.

2.2 Stiffness and Bonding Strength of Sea Ice Particles in DEM Simulation

To model the sea ice strengths with different particle sizes, the stiffness of sea ice particle can be set a function of particle size if the Young's Modulus is set as a constant.

The normal stiffness is determined with

$$K_{\mathrm{n}} = \frac{\pi E D}{4} \quad \textbf{[1]}$$

where E is the Young's Modulus of sea ice, D is the particle diameter.

In the previous study, the bonding strength of sea ice is set as a function of brine volume with (Ji, 2011)

$$\sigma_{\mathrm{b}} = \beta(v_{\mathrm{b}})\sigma_{\mathrm{b}}^{\max} \quad \textbf{[2]}$$

$$\beta = \mathrm{e}^{-4.29\sqrt{v_{\mathrm{b}}}} \quad \textbf{[3]}$$

where $\beta(v_{\mathrm{b}})$ is the reduction index, which is a function of brine volume, $\sigma_{\mathrm{b}}^{\max}$ is the maximum bonding strength between ice particles.

The temperature and salinity can be combined as one parameter of brine volume with (Frankenstein and Garner, 1967)

$$v_{\mathrm{b}} = S(0.532 + \frac{49.185}{|T|}) \quad \textbf{[4]}$$

where T is the ice temperature (°C), and S is the ice salinity(‰).

3. DEM Simulation of Sea Ice Flexural Strength

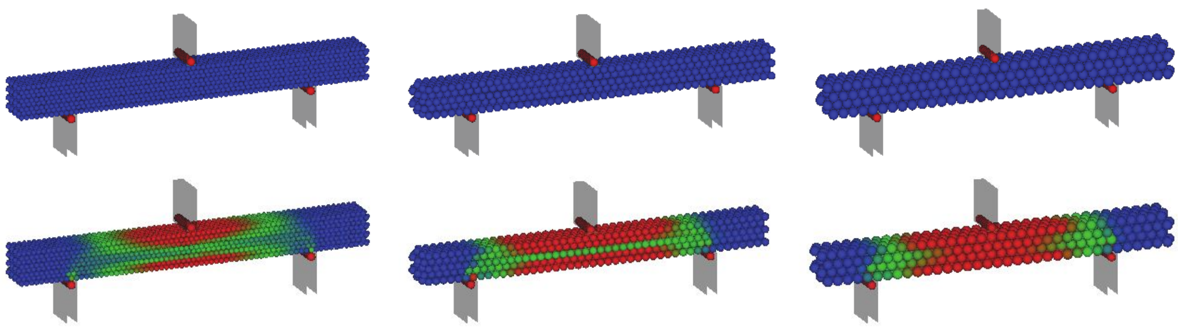
3.1 DEM Simulation with Regular Packing

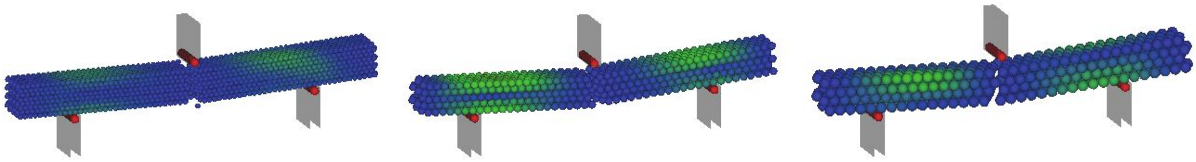
The flexural strength is simulated with DEM in regular packing via different particle sizes. The main computational parameters are listed in Table 1. The bonding strength of sea ice is set the function of brine volume, which can be determined under certain temperature and salinity by Eqs. [1]~[4].

Table 1. Computational parameters for DEM simulation of sea ice flexural strength.

Definitions	Symbols	Values
Sample size	$b \times h \times L$	70 mm×70 mm×700 mm
Distance of loading points	L_0	500 mm
Particle size	D	10, 15, 20 mm
Particle-particle friction	μ_{pp}	0.1
Particle-particle restitution	e_{pp}	0.9
Loading rate	u	0.1 m/s
Young's Modulus	E	10 MPa
Maximum bonding strength	σ_b^{max}	1.5 MPa
Ice salinity	S	0.1~7.0 ‰
Ice temperature	T	-20 ~ -1°C
Brine volume	v_b	0.001 ~ 0.149

Using T=-10°C and S=1.0‰, while the brine volume is 0.005 and the bonding strength is 1.095 MPa, the simulated bending failure processes are plotted as Fig.3 with different particle sizes. For example, if the particle diameter set as 15 mm, the simulated stress curve versus displacement is plotted in Fig.4. From this simulated curve, the flexural strengths can be determined as 2.15 MPa. With different brine volumes, which are determined with various salinities and temperatures, the flexural strengths are obtained with DEM simulated for different particle sizes. The results are plotted in Fig. 5. The fitted functions between ice brine volume and flexural strength are also listed in this figure with different particle sizes. We can find the strength is independent of the particle size.





(a) D=10 mm b) D=15 mm c) D=20 mm

Figure 3. Bending failure process of sea ice simulated with DEM using different particle sizes.

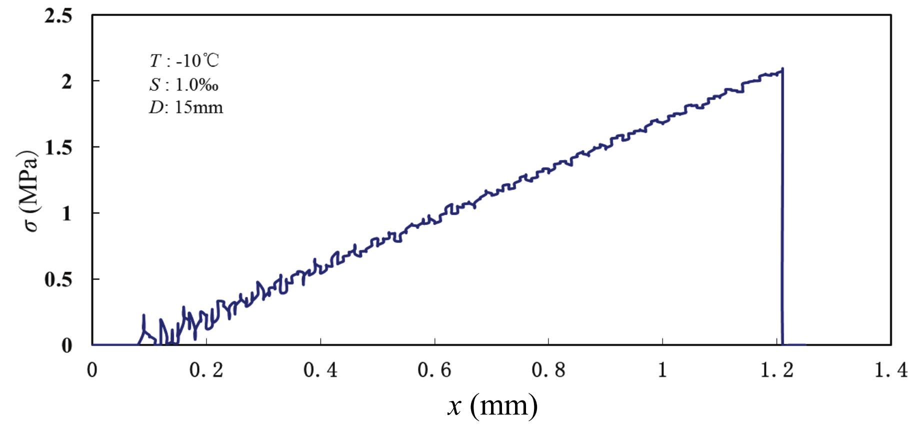


Figure 4. Stress versus (σ) displacement (x) of sea ice bending process simulated with D=15 mm.

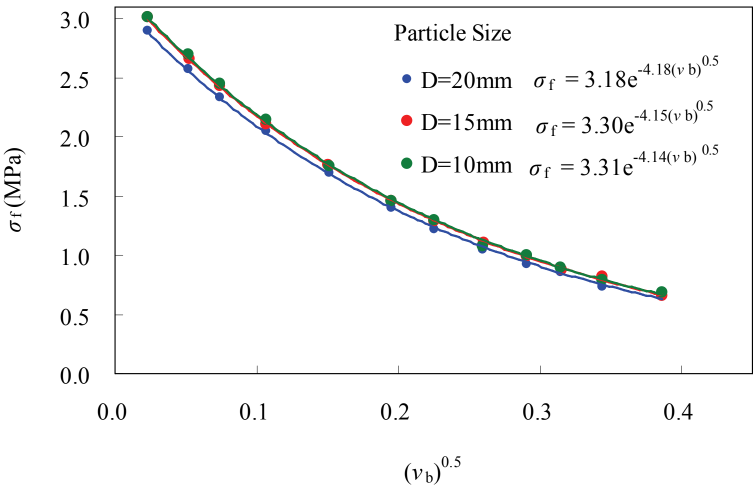
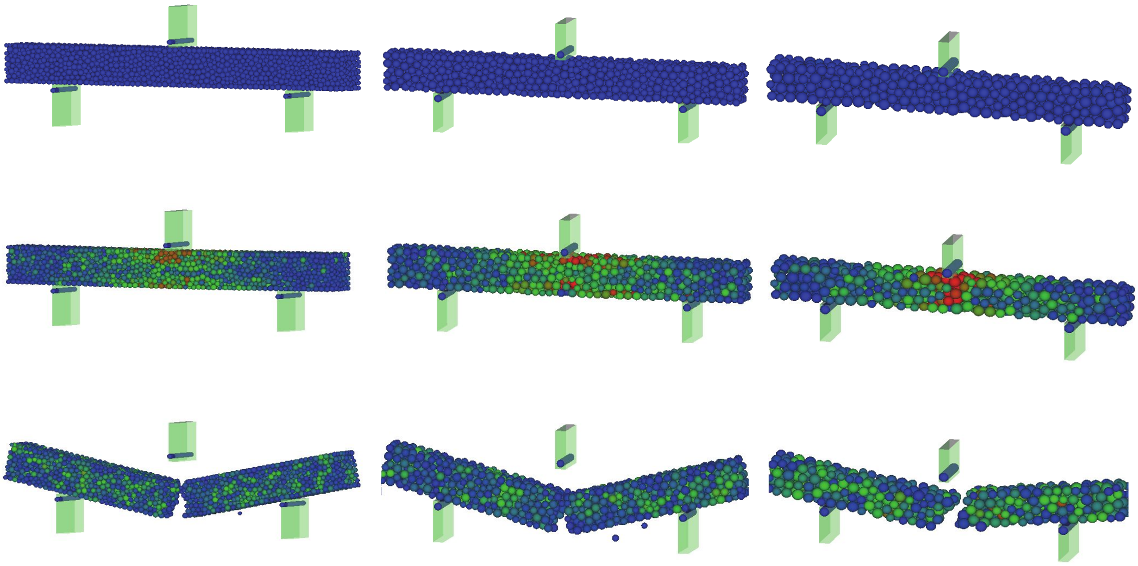


Figure 5. Comparison of sea ice flexural strengths under different particle sizes.

3.2 DEM Simulation with Random Packing

Considering the microstructure of granular sea ice, the random packing of particles is adopted to model the sea ice flexural strength. In the DEM simulation, the maximum bonding strength is set as σ_b^{max} = 2.5 MPa. Other input computational parameters are also listed in Table 1. Using T=–10°C and S= 1.0‰, the simulated bending failure processes with DEM are plotted as Fig.6 with different particle sizes. For these random packing of particles, the simulated flexural strengths are 2.43 MPa, 2.15 MPa, and 2.02 MPa when the mean size of particles are 10 mm, 15 mm and 20 mm, respectively. We can also find the simulated strengths decrease with increasing particle size, even the simulated values are very close.

With different brine volumes (i.e., salinities, temperatures) of sea ice sample, the flexural strengths are determined with DEM simulation using different particle sizes. The results are plotted in Fig. 7, and the fitted function is also listed in it. We can find the flexural strength of sea ice is almost independent of particle size even the strength of size D = 20 mm case is a little lower than that of others.



(a) D=10 mm (b) D=15 mm (c) D=20 mm

Figure 6. Bending failure process of sea ice simulated with DEM using different particle sizes.

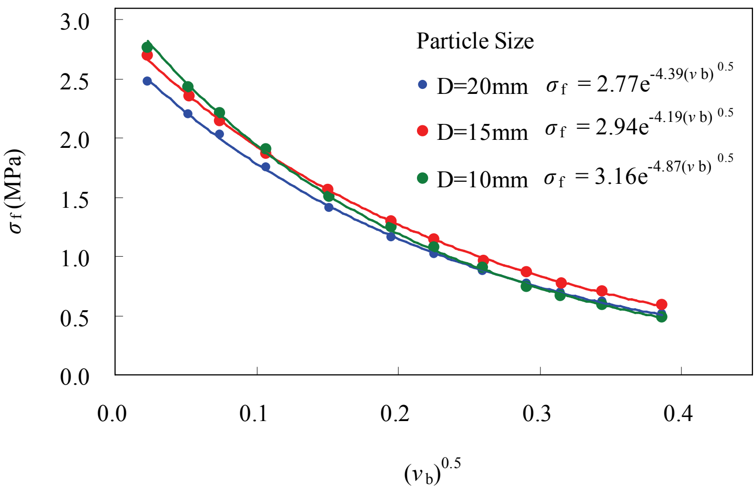


Figure 7. Comparison of sea ice flexural strengths under different particle sizes.

In the field experiments, the sea ice flexural strength was measured in different cold regions. Timco and O′Brien (1994) summarized 939 flexural strength tests and found out the flexural strength of sea ice has a negative exponential relationship to square root of brine volume. Ji et al. (2011) also determined the relationship between flexural strength and brine volume for the Bohai Sea. The results can be used to validate the DEM simulation data. We can find that the simulated result with regular packing is compared well with the experimental data. But the simulated data of irregular packing is a little larger than the experimental data. It can be modified with adjusting the maximum bonding strength in the DEM simulation.

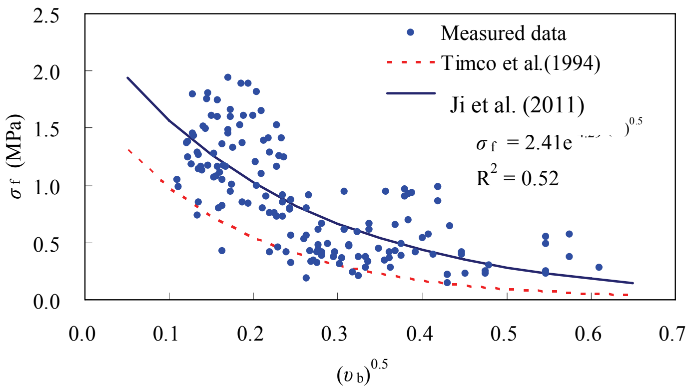


Figure 8. Sea ice flexural strengths with physical experiments (Timco et al., 1994; Ji et al., 2011).

4. Conclusions

In this paper, the microstructure of sea ice is discussed to construct the sea ice sample properly. Considering the granular and columnar structure of sea ice, the sea ice samples for bending test are constructed with regular and random packing, respectively. The sea ice flexural strengths are determined with DEM using different packing patterns and various particle sizes. The results show that the particle size affects the flexural strength a little. With increasing of particle size, the strength decreases slightly. The strengths simulated with DEM using regular and random packing patterns can be very close. But the bonding strength is higher in the random packing than that of regular packing. The simulated values compare well with the physical experiment data. In the future study, the DEM simulation should be improved more to describe the real physical process of sea ice failure.

Acknowledgements

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