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Interactive comment on "Strain response and energy dissipation of floating saline ice under cyclic compressive stress" *by* Mingdong Wei et al.

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This is an interesting paper about structured and well-described experiments on the cyclic loading of saline ice. In this work, novel and apparent test setup is used for testing of floating ice in the laboratory. Saline ice is produced in the laboratory in an unusual way and, surprisingly, showed a microstructure very similar to that of S2 sea ice. The growing and preparation method ensures that ice structure and the presence of brine in ice are not affected until the experiment begins. A fair amount of discussion is presented concerning the earlier work, suggesting reasons for the need in the testing of floating wet ice samples. The behavior of ice upon cycling is well predicted by the model. The key point of the paper is that warm wet floating ice behaves differently from cold dry ice. A weakness of the paper is that there is no clear answer/evidence

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on whether both water and temperature or only temperature play a major role in the mechanical behavior of ice under cyclic loading.

Overall, the paper is clearly written and provides new results. It is worthy of publication once some details have been clarified.

Re: We sincerely thank the reviewer for the constructive comments and valuable time devoted to improving our manuscript. We have modified our manuscript according to the comments. The majority of them led to modifications.

Specific comments:

1. Please, state that the sinusoidal waveform was used during cycling in the abstract (line 13) and introduction (line 61) for the readers' convenience. For example, "stress-controlled sinusoidal cyclic compression experiments" (lines 13-14).

Re: Thanks for the comment. We made the corresponding changes in the revised manuscript.

Lines 13 and 14, "stress-controlled sinusoidal cyclic compression experiments"

2. Lines 38-39: A reference to the study of ice fatigue in-situ tests led by Langhorne shall be provided. For example: * Bond PE and Langhorne PJ (1997) Fatigue behavior of cantilever beams of saline ice. J. Cold Reg. Eng. 11(2), 99–112; * Haskell TG, Robinson WH and Langhorne PJ (1996) Preliminary results from fatigue tests on in situ sea ice beams. Cold Reg. Sci. Technol. 24(2), 167–176 * Langhorne PJ, Squire VA, Fox C and Haskell TG (1998) Break-up of sea ice by ocean waves. Ann. Glaciol. 27, 438–442.

Re: We thank the reviewer for pointing this out. Corresponding changes are made in the revised manuscript.

Line 37, "...give insight into the fatigue of ice (Bond and Langhorne, 1997; Langhorne et al.,1998...)"

3. Lines 40-42: Strictly speaking, first cyclic loading experiments on freshwater ice were conducted in the forties: Kartashkin B.D., 1947. Experimental studies of the physico-mechanical properties of ice. Similarly, experiments on sea ice were firstly performed in the eighties: Tabata T, Nohguchi Y, 1980. Failure of sea ice by repeated compression.

Re: The literature review is modified in the revised manuscript.

Lines 40 and 41, "...have been performed since the forties (Kartashkin, 1947; Mellor and Cole, 1981) and on saline ice since the eighties (Tabata and Nohguchi, 1980..."

4. Lines 54-57: Reference to in-situ experiments by Langhorne shall be provided.

Re: Three pieces of literature by Langhorne, related to in-situ experiments, are added in the revised manuscript.

Line 54, "...in-situ experiments on floating ice (Langhorne et al., 2015; Smith et al., 2015; Wongpan et al., 2018)"

5. Lines 92-93: What was the reason for the temperature to be changed twice?

Re: Lower temperature (-14 degrees Celsius) was used for practical reason: make the ice grow faster. This was then changed to -10 degrees Celsius to perform the tests in a temperature such tests are often performed. The change was done well ahead of the actual experiments to ensure that the ice used for floating experiments had stable temperature and thermal gradient. We did not notice differences in the ice structure due to the change.

6. Line 99: What does "about" mean? Can authors provide standard deviation or standard error for their measurements?

Re: The standard deviations for the density measurements are provided in the revised manuscript.

Line 88, "...and their densities were 886±19 and 879±16 kgÂům-3, respectively"

7. Line 127: What was the accuracy of temperature measurements? Thermistors and thermocouples usually have an accuracy in the range from about ±0.3 to ±2.5âŮęC. In this case, the resolution is not important for the manuscript and shall be replaced with accuracy.

Re: We agree. The accuracy of temperature measurements is ±0.5 degrees Celsius. This information is supplemented in the revised manuscript. Thanks for this constructive comment.

Line 112, "...and an accuracy of ± 0.5 degrees Celsius"

8. Line 137: Again, what is the accuracy of LVDT? Is it more important than a resolution?

Re: The description is updated in the revised manuscript (line 144). We agree that the accuracy of LVDT (0.001 mm) is more important than the resolution (0.0001 mm). The "resolution" described in the original manuscript actually refers to the "accuracy". Apologies for this clerical error.

Line 120, "...with a measurement range and accuracy of 2 and ± 0.001 mm, respectively"

9. The stress during cycling was as low as 0.005-0.085 MPa (line 327). This range seems to be very low. What was the accuracy of a load cell and how accurate the machine (actuator) could control load-limits? Could the test setup ensure accurate cycling between 0.005 and 0.085 MPa? This should be commented on in the text.

Re: We modified the text to comment on this. Since our specimen size was 0.6 m × 0.3 m × 0.1 m, the force applied for stress amplitude 0.005–0.085 MPa was 0.15–2.55 kN. The accuracy of the load cell was ±5 N; thus, there was no severe error on the cyclic stress values and we have a reason to assume the cycling was accurate.

Line 106, "The load cell had an accuracy of ± 5 N, which is sufficient for all stress levels and cycles of the experiments here"

Line 305, “Nominal cyclic stress of 0.005–0.085 MPa is low, but the setup could achieve it: With the accuracy of the system, the actual stress applied to the specimen was 0.005 (±0.001)–0.085 (±0.003) MPa”

10. When using words “linear loading” you always should be careful since ice never behaves purely elastically (linearly); an inelastic component (though minor) is always present.

Re: We agree. The statement was actually referring to the application of a linear loading ramp, not the response of the ice. For clarity, the related sentences have been modified as follows.

Line 144, “the duration of the initial loading ramp was fixed to be 1 s”

11. Lines 212-213: References to other works that show similarly that the hysteresis loop area increases with an increase of the cyclic period shall be added: * Weber LJ and Nixon WA (1996) Hysteretic Behavior in Ice Under Fatigue Loading. Proceedings of the 15th International Conference on Offshore Mechanics and Arctic Engineering. 75–82 * Murdza A, Schulson EM and Renshaw CE (2018) Hysteretic behavior of freshwater ice under cyclic loadingâĂŸ ′r: preliminary results. 24th IAHR International Symposium on Ice. Vladivostok, 185–192 * Cole DM (1990) Reversed direct-stress testing of ice: Initial experimental results and analysis. Cold Reg. Sci. Technol. 18(3), 303–321.

Re: Missing references have been added in the revised manuscript.

Line 187, “. . .consistent with earlier studies (Cole, 1990; Murdza et al., 2018; Weber and Nixon, 1996)”

12. It is mentioned in Lines 208-211 that the area of the hysteresis loop is decreasing until a “steady-state” is reached. Does this happen only during the first set of loading (T=1s) or during any subsequent loadings as well? (especially after 15 min of recovery in the case of dry ice)? If some cycles are needed to reach a steady-state condition

every time (for example after relaxation) then is N=4 cycles at T=1000s for dry ice and N=1 cycle for wet ice enough to get a steady-state as mentioned in line 225?

Re: In brief, the phenomenon happened in all the dry experiments. However, the larger the T value, the less the number of cycles required to reach the "steady-state". This is shown by Figure 9, in which there are 5 or 6 cycles before the experiment with T=100 s reaches the "steady-state", while the experiments with T = 500 and 1000 s only require two cycles and one cycle, respectively, to achieve the "steady-state". An important reason why the dry specimens require some cycles to reach the "steady-state" is the 15-minute recovery period before each experiment. In the floating ice experiments, the cyclic loads with increasing periods were applied to the specimen in a continuous manner – loading with one period after another without a recovery period. After some initial loading cycles of T = 1 s, the ice samples maintained a relatively steady state in subsequent cyclic loads (Figures 10 and 11). For example, the areas of the two hysteresis loops at T = 100 s are very similar, having a much smaller difference than those of the first two hysteresis loops in the dry experiments with T = 100 s. Therefore, it is believed that N = 1 can be used for the floating experiment with T = 1000 s. In addition, the good agreement between the experimental and modeling results also shows the reliability of the experimental scheme and test results to a certain extent. We modified the text to discuss this, as shown below.

Line 183, "For example, the hysteresis loops after the first stress cycle in the dry experiment with T = 1000 s are similar; N = 4 is enough for the dry specimen at T = 1000 s to show steady-state response"

13. It is emphasized through the manuscript on the importance of considering warm floating ice for the experiments, in contrast to cold dry ice. In addition, the conclusion that water and temperature have a greater effect on elastic modulus than salinity is made. It is not a big surprise that "warm" ice behaves differently than "cold" ice and the temperature of ice affects elastic modulus. Therefore, do you think that if you repeat your experiments on dry ice at about -2.5âŮęC (average temperature of wet specimens

based on line 153) instead of -10âŮęC it would behave similarly to wet specimens? In this case, no additional brine will freeze during the storage as mentioned in line 410. Is it possible that brine migration during cycling affects mechanical properties? Perhaps, there is no need to conduct experiments on floating ice but rather increase the ice temperature. If authors think similarly, they should state it more clear because the reader may get the impression that both floating and warm conditions are equally important during cyclic loading of ice (which may not be true). I think it would be interesting to compare the results of both wet and dry ice of similar temperatures.

Re: Earlier laboratory work on ice has mostly focused on dry, cold and isothermal ice. Here we wish to draw attention to the fact, that the results from such experiments may not apply directly on saline ice in its natural conditions, that is, when ice is floating in water – and also to the fact, that the experiments where this type of conditions are mimicked in the laboratory can be performed. We do not aim to differentiate between the importance of the different factors on the ice behavior and hope this is now more clearly stated in the manuscript. In brief, our goal was (i) to present our methods used to perform laboratory-scale experiments on ice in its natural conditions and validate their applicability with floating ice experiments and commonly used test conditions (dry experiments), (ii) to report experimental results from cyclic loading tests on floating and dry specimens using different salinities, stress amplitude and loading-unloading periods, and (iii) to analyze the test results of the floating ice and dry ice specimens using a physically based model.

Thus, the original intention of this study is not to investigate the effect of temperature and floating condition on ice behavior. Probably the previous version of our manuscript made some excessive comparisons between warm floating ice and cold dry ice and some sentences were somewhat misleading in that regard. The revised manuscript clarifies our goals. For example, we reorganized the conclusions around the two themes of this article: experimental methods and material modeling of floating ice. We also avoided using "wet experiments" to refer to the floating ice experiments, in

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order to avoid the misunderstanding that here we are studying the effect of water on ice behavior. We thank the reviewer this constructive comment.

Comparing the results of both wet and dry "warm" ice of would be interesting, but would need another extensive experimental campaign. Inspired by the comments by the reviewer, we plan to conduct experiments on this in our future work. In fact, research on the effect of water is scarce, which also shows the necessity of developing experimental equipment for floating ice tests (as done here), which will help to reveal the mechanical properties of floating ice more deeply in the future.

14. Generally, a paper should be short and laconic but "full" in context. I suggest the authors make their manuscript shorter where it is possible by removing unnecessary parts. For example, in lines 100-101: "The specimens used in the dry experiments (Figure 2a and 3) were sealed in plastic bags and stored in a freezer for 1-2 days before testing. The freezer temperature was set to -10âDËĞ C." can be replaced as: "The ËĞ specimens used in the dry experiments (Figure 2a and 3) were sealed in plastic bags and stored in a freezer at -10âŮęC for 1-2 days before testing.".

Re: Thanks for this constructive comment. We have modified the manuscript by removing some unnecessary parts.

15. Figure 4: Ice salinity shall be mentioned in the caption.

Re: Ice salinity is now provided in the caption of Figure 4.

Caption of Figure 4, "...thin sections of the ice (salinity: 5 ppt) ..."

16. Line 89: The verb "nucleated" fits better than "generated".

Re: Thanks for pointing this out. Since this part of description is unnecessary, according to your Comment 14, we deleted it.

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