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The Cryosphere
Discussions

Interactive comment on "Elastic-viscoplastic characterization of S2 columnar freshwater ice" *by* Iman E. Gharamti et al.

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We thank the reviewer for carefully reviewing our work and making constructive comments. We appreciate all the time and efforts he/she put in their thorough review. All the reviewer's comments were considered in the revised manuscript. Detailed answers to each comment are given below.

1. RC2: Page 1, line 14 – The eventual goal of these experiments seems to be to better describe or model ice loads during sea ice floe interactions with structures in the Arctic. As the authors mention the deformation modes are quite complex during ice-structure interaction, but there is no literature cited on this work. For example, Claude Daley at MUN has done experimental and modeling work on this using ice indentation experi-

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ments on structures, which seems to be the most relevant mechanism for transfer of ice loads onto structures. One would rarely imagine a floating ice flow to be subjected to mode I tension. Please add more description to the introduction about what experimental data is available, what motivated the current experimental study and why mode I fracture experiments are relevant in the context of ice-structure interaction.

Authors: Many of the comments by the reviewer deal with sea ice, Arctic and engineering relevance. It appears that the introduction of our submission was unfortunately giving an impression that our work on creep deformation and fracture of freshwater ice has direct application in sea ice and Arctic engineering. That is not the case and we apologize for the confusion caused. Deformation and fracture of ice are highly dependent on salinity, temperature, strain rate, sample size, grain type, and grain size. Our paper reports results from laboratory experiments which were conducted to study the creep and fracture of warm, floating, columnar grained S2 freshwater ice. The work is directly relevant to a number of problems on freshwater ice in rivers and lakes [1] and the Baltic Sea which is almost freshwater ice. However, it has also general relevance to the creep and fracture of a quasi-brittle material. Unless we restrict our interest on the short time scales where only elastic response is relevant, the creep deformations must be modeled to obtain the true fracture behavior. In materials with time-dependent properties, the fracture and creep deformations are coupled.

Mode I loading is rather common in a number of ice problems. For example, sea ice floes fracture when in contact with ships and offshore structures or when loaded by waves, river ice fractures during interaction with bridge piers, and thermal cracks form in lakes and reservoirs.

2. RC2: Page 2, line 26 – Why has it become increasingly important to use time-dependent constitutive modeling. When was it less important? Perhaps, the authors are referring to recent drastic changes in the Arctic sea ice. The sentence here is rather vague.

Authors: We did think of the warming climate and thus warming ice which may potentially increase the importance of creep deformation and apologize for not writing this clearly. In addition, the applications like river ice breakup happen in late spring and the ice is very warm. For that reason, the creep deformations are very important but historically cold ice has been studied typically.

3. RC2: Page 2, line 30 – While it is true that ice sheet and glacier modelers use viscous creep law, the terms long term and short term are vaguely defined. As my research has found, sometime a few hours is all that takes for viscous behavior to dominate, which is not really that long term. Please explain clearly that short time scales you mean are seconds or minutes or hours.

Authors: We agree that "long" and "short" are vaguely defined terms and have different meaning in different contexts. It is also not correct to imply that this study is relevant to glaciers. We are studying columnar grained ice not very fine grained equiaxed snow ice.

4. RC2: Page 3, lines 65 to 70 – The study's aims are noted here. However, there is an important discussion missing here about viscoelastic fracture mechanics. The concept of fracture toughness or critical stress intensity factor is only well defined for linear elastic solids or elasto-plastic solids with small scale yielding. The authors should state and explain the definitions. Of the apparent fracture toughness K_Q and the loading rate Kˆdot, and why they are relevant quantity to ice mechanical behavior. What are the specific assumptions made about the ice viscoelastic behavior. Refer to any experiments and modeling studies in the literature that establish the theory of fracture in time-dependent materials.

Authors: We will add a discussion on time-dependent fracture. The reviewer is correct. It has been known that the viscoelastic fracture mechanics [2] is on a firm foundation so long as a finite cohesive zone is attached to the traction-free crack tip. The one-parameter fracture mechanics encompassed by the K_Q notation is not applicable [3]

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and will be removed. Although Kˆdot was used for comparative measure of the loading rate, it will be replaced by the measured time of failure in each experiment. The K_Q plot will be replaced by a plot of the peak loads. We hope that any confusion will be cleared up then.

5. RC2: Page 3, lines 75 to 85 – The scale of these experiments is truly impressive, however, referring to my previous why is mode I fracture relevant for ice-structure interaction. Aren't sea ice floes breaking up due to compression and plate buckling processes. Please explain the motivation for these experiments and how it can be used in largescale modeling of ice-floe structure interaction. For example, will this study provide necessary parameters for discrete element modeling of sea ice-structure or ice-ship interaction.

Authors: Please see our response to Comment 1. Our main concern here is how tensile cracks develop in columnar freshwater ice under the applied loading.

6. RC2: Page 3, line 85 – The top surface temperature is noted as -2 C, but in Figure 2a the temperature below the surface is around -0.3 C. I am confused, please explain.

Authors: We apologize for the confusion. During the experiments, the ambient temperature in the laboratory was kept at -2 C. The temperature profile within the ice is shown in Fig. 2a in the manuscript. The text is edited to clear this confusion.

7. RC2: Page 3, line 86 – Please provide some more description of the experimental setup, ice growth etc as we still do not have access to your paper in press. Why does the grain size increase with depth? Also, how realistic is this for sea ice as opposed to stagnate lake ice with no waves.

Authors: The paper by Gharamti et al. [4] is now published. The cited reference is edited. The grain size increasing with depth is the characteristic of columnar S2 ice [5]. Michel and Ramseier [5] classified lake and river ice according to the size, shape and orientation of the crystals and the environmental factors causing them. For quiet lakes subject to no wind and no snow falling, S1 ice with vertical c-axis orientation will form. The paper will be revised with a thorough discussion of the grain size effect.

8. RC2: Page 3, line 90 – The experiments report the load values and peak loads. However, it would be useful from a modeling perspective to get crack initiation stress. Is it possible that this sort of information can be extracted and reported from experiments. This will make the paper's results useful to those modeling sea ice-structure interaction.

Authors: We cannot determine the crack-initiation stress in these creep and cyclic-recovery experiments. The crack-initiation stress can be computed for the monotonic DC tests [4] because the stress-separation curve was derived for the DC tests. However, for the LC tests here, the stress-separation curve is unknown.

9. RC2: Page 4, line 95 – How do the applied load rates and load levels related to real ice floes. A bit more justification is needed to establish the rationale for testing.

Authors: We are mainly concerned here with the tensile cracks growing in columnar freshwater ice. We could be studying the bearing capacity of lake ice, the splitting of lake ice by an ice breaker, the breakup of river ice, and similar applications in the Baltic sea etc. Ice in nature is loaded through a wide range of time scales. The loading was chosen to reflect one time-dependent response that can be encountered. The loading rate used is similar than used in earlier sea ice studies and thus allows comparison of these two materials.

10. RC2: Page 4, line 103 – I am failing to understand the purpose of creep loadings. If the creep loads were kept small so that no damage nucleates and with recovery periods, there should not affect. In fact, this is what is observed with the results.

Authors: The creep-recovery tests in the time-domain were conducted to study the response of the ice under several load steps, which has not been studied before on freshwater ice. Previous studies have concentrated either on cyclic loading in the frequency domain [6,7] or on a single load step [8]. The main reason the loads were kept small is to avoid damage [9] because we are not modelling damage. The creep/cyclic-recovery sequence did affect the accumulation of the viscoplastic component of the crack opening displacement (Fig. 11 in the manuscript).

11. RC2: Page 4, line 108 – Once again how do these cyclic load levels and loading rates related to the physical setting. Are these in any way representative of the ocean wave loads on sea ice floes?

Authors: Please see our response to Comment 9.

12. RC2: Page 5, Equation 2 – Replacing the stress and strain with load and displacement is valid only for linear behavior. Has Schapery's model used with load and displacement before in any literature?

Authors: The same modelling for load and displacement has been used by Adamson and Dempsey [10]. The modelling works very well, and the CMOD was predicted correctly until the crack began to propagate.

13. RC2: Page 7, line 195 – What is the purpose of the modeling and parameter estimation. I ask this because I work in ice fracture modeling and cannot really see how these experiments can improve the fracture models.

Authors: The approach we have used – fitting a model with experimental data by using optimization – is common in fracture models with several parameters. Pure experimental methods to determine these parameters have proven extremely difficult and indirect methods, based on parametric fitting, has been developed and used instead [11]. In addition, the Schapery model can fit successfully both creep-recovery and cyclic loading.

14. RC2: Page 7, line 204 – How is the weight function approach applied? Numerical evaluation of integrals with weight function approach can lead to inconsistencies. Why not use the displacement correlation method directly using COD and CMOD and NCOD?

Authors: A lot of work has been done on the weight function of an edge-cracked rectangular plate [12] used in the current experiments. The accuracy of this weight function was derived, assessed and thoroughly validated by comparison with other published data. The displacement correlation method cannot be used because of the presence of creep. The deformations are affected by creep and by possible growth of the crack.

15. RC2: Page 8, line 213 – Figure 5a needs more explanation. In viscoelastic materials, the peak load increases with loading rate. Please define precisely what Kˆdot is and why the peak load decreases as you increase Kˆdot. Also, defined what you mean by failure load. Is it the same as peak load? If so, then just use one terminology consistently.

Authors: In these experiments, the failure load is the same as the peak load. We are not including K_Q and Kˆdot in the analysis anymore.

16. RC2: Page 8, line 228 – What are the differences in the post-peak load curves that should be identified. Is it the oscillatory nature of load displacement curves in cyclic sequences? A better explanation would be useful.

Authors: The decay of the load for the creep-recovery tests (Fig. 5b in the manuscript) took a much longer time than that for the monotonic tests (Fig. 5a in the manuscript). Unfortunately, the reason for the oscillatory nature of the signal is unclear to us.

17. RC2: Page 8, line 235 – The authors state "It is clear from Figs. 7b and 8b : : :" How is it clear? The writing style is a bit confusing.

Authors: The measured displacement records in Figs. 7b and 8b show the absence of the viscoelastic component. A typical creep displacement-time record displaying the three displacement components (elastic, viscoelastic and viscous) looks as shown in Fig. 1 here. By simply comparing Fig. 1 here with each creep/cyclic-recovery sequence in Figs. 7b and 8b in the manuscript, one can deduce that the viscoelastic displacement and the viscoelastic recovery were absent from the current data.

18. RC2: Page 9, line 243 – I only know of the Maxwell model and the generalized Maxwell model. What is a simple Maxwell model?

Authors: We meant a Maxwell model composed of a nonlinear spring and a nonlinear dashpot. To avoid confusion, this statement is deleted in the revised text.

19. RC2: Page 9, lines 247 to 259 – This whole paragraph should be written as a separate discussion section. Based on my recollection the experiments of Sinha and Cole involved compression loads and not tension loads, and there were not really on pre-cracks ice slabs. This lead to the question on why delayed elastic effect was not there? However, it is not clear why this is even an important question in the context of ice-structure interaction.

Authors: The authors thank the reviewer for his/her recommendation. The authors created a separate discussion section.

20. RC2: Page 267 – The statement "When the specimen dimensions are several meters, apparently viscoelasticity is not an important deformation component" is poorly explained. Also, what is the consequence of this finding? Is the author suggestion that one can just use elastic model for sea ice-interaction? Is there any relevance of these results for floating ice shelves, which are much larger than ice floes?

Authors: Our experiments suggest that for the large sample size and the kind of ice studied (very warm freshwater ice) under the loading applied, the response was elastic-viscoplastic. More experiments are needed to make more general conclusions.

21. RC2: Overall, I am not clear on what the broader purpose of the paper is? Why did the author's select the specimen size and loading rates they used. Why specifically test creep/cyclic recovery? How is this work relevant to the motivation mentioned in the first paragraph of the introduction – interaction of ice floes with structure. How to use the data and findings of this paper in any future modeling analysis. A comprehensive revision of this article is needed and I recommend including a discussion section to

address the implications of this research.

Authors: Please see our response to Comment 1.

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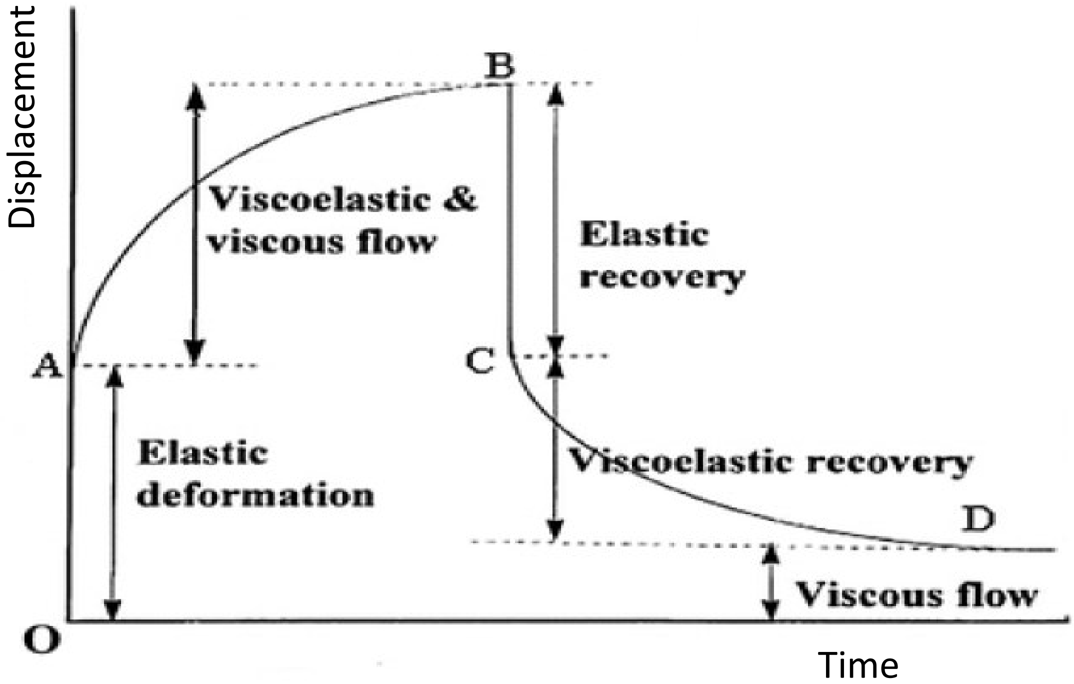

Fig. 1. General displacement-time record for a creep-recovery test. The elastic, viscoelastic, and viscous (viscoplastic) components are marked.

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