Authors' response file

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April 13, 2021

Replies to reviewers' comments

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

1. General modifications in the revised manuscript

- Added text is displayed in red.
- Deleted sentences are marked with a red strikethrough.
- Fig. 7d is added.
- New references are added: Dash et al. (2006), Gasdaska (1994), Muto and Sakai (1998) and Rist et al. (1996).

2. Reviewer 1 comments

Two findings: (i) creep and cycling sequences had no clear effect on failure load; and (ii) unlike in all past work where both recoverable (anelastic/delayed elastic/viscoelastic strain) and non-recoverable (viscoplastic) deformation have been found to contribute to creep of ice, significant viscoelasticity was not detected."

1. Finding (i) , with one proviso, is worth publishing. Earlier work (Rist et al. (1996, Annals of Glaciology, vol. 23, p.284), not referenced in this manuscript, hinted at an effect; now there appears not to be one. The proviso, in keeping with the stated objective of assessing fracture properties, is that this finding should be presented in terms of a fracture property, namely fracture toughness. Failure load is insufficient. The finding was presented in that way in the original manuscript (original Fig4). Why the change?

We thank the reviewer for his comment. However, the authors edited the revised manuscript and deleted the fracture toughness data in accordance with the comments given by the second reviewer of the first review round. The concept of fracture toughness or critical stress intensity factor is only well defined for linear elastic cases. The one-parameter fracture mechanics is not applicable in the context of time-dependent fracture mechanics, which is the current study case.

The authors replaced the fracture toughness plot by a plot of the peak/failure loads. The fracture toughness is function of the peak/failure load and geometry. As the tested specimens are of the same geometry, size, and crack length, the failure load gives a good indication about the effect of creep/cyclic loading on the fracture behavior.

We thank the reviewer for mentioning a paper by Rist et al. The authors checked the paper's relevance to the current study and decided to cite it in the current manuscript.

2. Finding (ii) is troubling. Prior work , correctly cited, revealed that viscoelasticity contributes to the creep of ice. Now, no significant anelasticity is detected. Why not? The authors point to differences in specimen size, temperature and grain size, although how those factors could account for the difference is not made clear. Instead, could the explanation reside in the experiment and analysis itself? Unravelling the various contributions to time-dependent deformation, even when experiments are made under uniaxial states of stress, is not easy. Here, the stress state is only approximately uniaxial and the unravelling is performed through mathematical manipulation to optimally fit model to data—a procedure the authors justify with the statement (lines 160-2): "This approach of fitting a model with experimental data is common in fracture models with several parameters. Pure experimental methods to establish these parameters has proven extremely difficult. . . .". To conclude (lines 344-5) from this rather tortuous approach, justified by what could be read as an excuse, that the response of the ice was overall elastic-viscoplastic is questionable. The conclusion is not credible. Worse, it muddies the picture of the time-dependent deformation of ice.

The conclusion of no significant viscoelasticity is **MERELY** based on the experimental observations and measurements and **NOT** on the numerical modelling. The measured displacement-time records (Figs. 7b and 8b in the manuscript and Fig. R1a here) displayed clearly a constant creep rate that usually dominates in the secondary (steady-state) creep stage. This indicates an instantaneous transformation from the primary (transient) stage to the steady-state regime, which resulted in permanent (unrecoverable) displacement. Accordingly, the viscoelastic component which should develop in the primary creep stage was insignificant. The measured records resemble the response of a Maxwell model, consisting of a nonlinear spring and nonlinear dashpot, to a constant load step (Fig. R1b). The accumulation of the viscoplastic component and the insignificant viscoelasticity can be also seen from the hysteresis loops (Fig. 6 in the manuscript).

The results of the initial optimization trials supported the experimental observations. The viscoelastic component $\delta^{ve}_{\mathrm{CMOD}}$ had no effect on the final fit between the data and the model (Fig. R2). The optimization algorithm fine-tuned κ (see Eq. 11 in the manuscript) to a very small number (10^{-18}), indicating that the best model-data fit is attained when the viscoelastic term goes to zero. The final optimization runs were then carried out without considering the viscoelastic term in the numerical fitting.

This is a novel result for any type of ice. In comparison with earlier freshwater ice studies, most of the previous work (cited in the manuscript) used colder freshwater ice and smaller samples and reported significant viscoelasticity. In comparison with sea ice, the measured response of the current ice is different from what has been reported for sea ice. For example, Adamson and Dempsey [1] studied warm and floating sea ice, used similar size and testing setup as the current study, and reported a different behavior (Figs. R1c and R1d); the measured data showed a significant viscoelastic component by the decreasing strain rate.

The authors respect the reviewer's reluctance to accept the conclusion of no significant viscoelasticity. This is understandable as the conducted tests are new and unique and no similar results have been reported in the literature. The authors discussed (Section 5 in the manuscript) the possible factors that could have contributed to the observed behavior. More details are added in the revised manuscript. Viscoelasticity occurs normally when the internal stresses developing during loading at the local stress concentrations (triple points and grain boundary ledges) accommodate the grain boundary sliding and causes sliding in the reverse direction, giving rise to the recoverable component after unloading. However, in our case, the measurements showed that the grain boundary sliding produced permanent deformation. Several reasons can be pointed out, related to the temperature, microstructure, and nonlinear mechanisms in the process zone. Most importantly, our experiments used warmer ice and larger sizes than previous freshwater studies.

Concerning the effect of temperature: the warmer the temperature, the more liquid on the grain boundary. The high homologous test temperature (top ice surface $\approx$ -0.3 C) causes liquidity on the gain boundaries [2]. The intergranular melt phase on the grain boundary renders ice as two-phase polycrystal and significantly influences the creep and recovery process. In fact, the grain boundary sliding then consists of two processes: 1) the sliding of grains over one another and 2) the squeezing-in/out of the liquid between adjacent grain [3]. The shear behavior of the liquid film is function of its properties (thickness and amount). The presence of this liquid at the triple points and the boundary acted as a resisting obstacle for the grains to shear and deform back to their original form, resulting in the viscoplastic deformation.

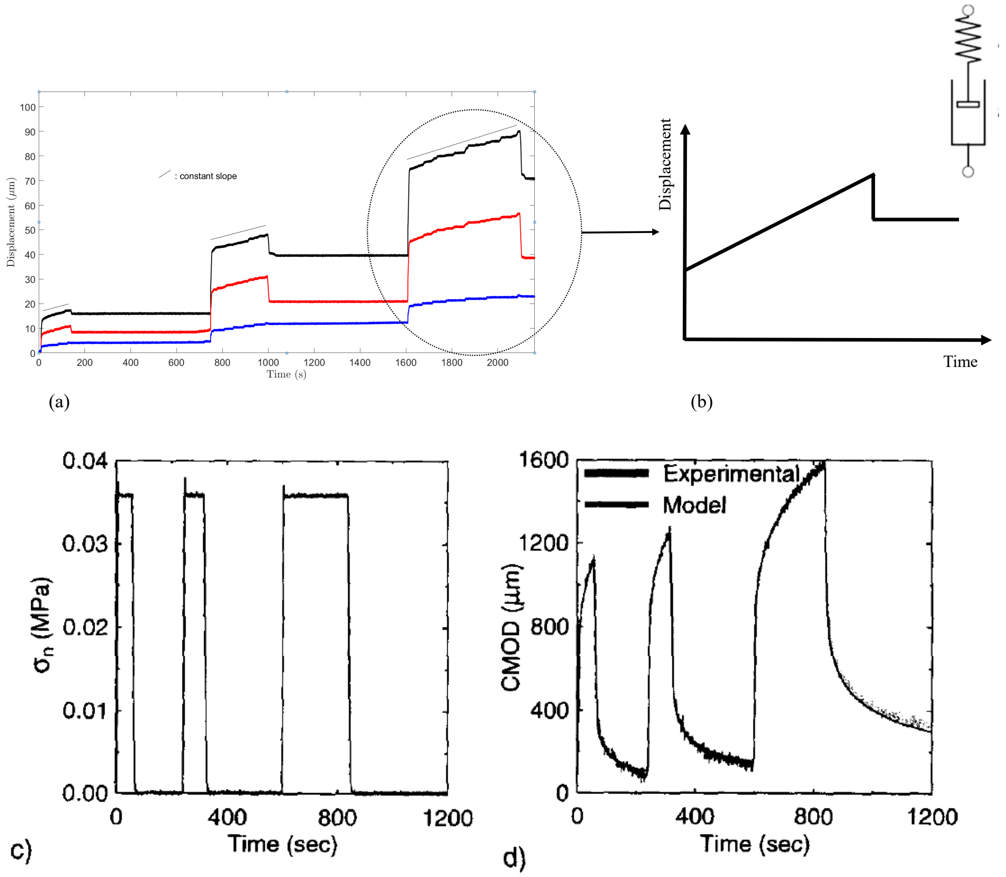
The microstructure (grain size, crystalline texture) could be another contributing factor. Sinha [4] developed a nonlinear viscoelastic model, incorporating the grain size effect, to describe the high-temperature creep of polycrystalline materials. He concluded that delayed elastic strain exhibits an inverse proportionality with grain size. This suggests that the grain size (3-10 mm, Fig. 2b in the manuscript) of the ice samples is coarse enough not to produce any measurable viscoelastic deformation under the testing conditions. It is also probable that for this grain size, there was not enough local concentration points to arrest the grain boundary sliding and drive the recoverable and reverse sliding. In addition, [5] discussed that regularly ordered and packed microstructures limit the amount of sliding and rearrangement and lead to less anelastic strain. The ice growth in the Aalto Ice tank was very controlled and resulted in homogeneous ice sheet.

Finally, the nonlinear mechanisms in the process zone possibly relieved the internal stresses that are needed to accommodate the grain boundary sliding and drive the recovery. This implies that any microstructural damage that occurred during loading manifested as permanent deformation at the end of the test.

Concerning the specimen size, our experiments used larger sizes than previous freshwater studies. Testing the effect of size requires a test program that use different specimen sizes while keeping all the other conditions fixed. All the above-mentioned factors may have contributed to the measured response. However, the question as to which factor influenced mostly the measured behavior is an important research question and requires more experiments.

3. Reviewer 2 comments

1. While I recognize the novelty of the experimental studies and the usefulness of the collected data to the



(a)

(b)

Figure R1: (a) Measured displacement-time record of RP16. (b) Typical response of a Maxwell model, consisting of a nonlinear spring and nonlinear dashpot, to a constant load step.(c) Creep-recovery loading profile and the (d) corresponding crack-mouth-opening displacement measured record for a similar testing setup of in-situ first year sea ice [1].

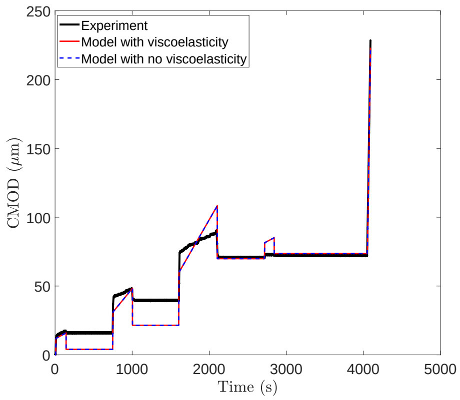


Figure R2: CMOD-time record: Schapery's model with and without viscoelasticity versus the experimental data.

Cryosphere community, I still feel that the authors did not go far enough in terms of explaining how this data or the Schapery model can be used. Please add specific discussion about how this experimental data can be used by modelers and/or any planned future work.

The main concern from the conducted experiments is to gain a better understanding of the creep and fracture behavior of warm, foating and columnar grained freshwater ice. With the warming climate and thus warming ice, we are interested in creep deformations and how cracks develop in columnar freshwater ice.

Schapery's model has been singularly powerful and successful for this type of loading [1, 6]. Other analyses and approaches didn't do as well. For instance, the experimental data by LeClair [6] was modelled by Schapery's model [6] and by a physically-based FE model [7]. While the physical model did a reasonable job of modelling the data, Schapery's straight-forward model did a better job. However, before a general well-calibrated form of Schapery's model can be presented for columnar freshwater ice and used by future modelers, a lot of experimental work needs to be conducted at different testing conditions: temperatures, loading rates, sample sizes, etc.

2. The major finding is that viscoelasticity of S2 columnar ice is not significant because there is no delayed elastic recovery observed in the experiments (Figs. 7b and 8b). Therefore, the authors conclude that ice samples showed elastic-viscoplastic material behavior. The other reviewer seemed to be critical about this. The authors explanation "Further studies are needed to confirm this result and to find explanations for the behavior" is honestly a bit underwhelming. Could the authors instead explain what sort of further studies are necessary to confirm and find explanations. Can the authors test smaller colder samples and do a quick check? Considering that is a significant conclusion, it is essential that the authors unequivocally establish this.

The conducted large-scale tests are unique; no similar tests for columnar freshwater ice have been performed earlier. The obtained ice response is different from what has been reported earlier for freshwater ice. It is a novel result for any type of ice. In comparison with earlier freshwater ice studies, most of the previous work (cited in the manuscript) used colder freshwater ice and smaller samples and reported significant viscoelasticity. In comparison with sea ice, the measured response of the current ice is different from what has been reported for sea ice. For example, Adamson and Dempsey [1] studied warm and floating sea ice, used similar size and testing setup as the current study, and reported a different behavior (Figs. R1c and R1d); the measured data showed a significant viscoelastic component by the decreasing strain rate.

The authors discussed (Section 5 in the manuscript) the possible factors that could have contributed to the observed behavior (no significant viscoelasticity). More details are added in the revised manuscript. Viscoelasticity occurs normally when the internal stresses developing during loading at the local stress concentrations (triple points and grain boundary ledges) accommodate the grain boundary sliding and causes grain boundary sliding in the reverse direction, giving rise to the recoverable component after unloading. However, in our case, the measurements showed that the grain boundary sliding produced permanent deformation. Several reasons can be pointed out, related to the temperature, microstructure, and nonlinear mechanisms in the process zone. It is important to emphasize that in comparison with other tests, our ice specimens were large and very warm.

Concerning the effect of temperature: the warmer the temperature, the more liquid on the grain boundary. The high homologous test temperature (top ice surface ≈ -0.3 C) causes liquidity on the gain boundaries [2]. The intergranular melt phase on the grain boundary renders ice as two-phase polycrystal and significantly influences the creep and recovery process. In fact, the grain boundary sliding then consists of two processes: 1) the sliding of grains over one another and 2) the squeezing-in/out of the liquid between adjacent grain [3]. The shear behavior of the liquid film is function of its properties (thickness and amount). The presence of this liquid at the triple points and the boundary can act as a resisting obstacle for the grains to shear and deform back to their original form.

The microstructure (grain size, crystalline texture) could be another contributing factor. [4] developed a nonlinear viscoelastic model, incorporating the grain size effect, to describe the high-temperature creep of polycrystalline materials. He concluded that delayed elastic strain exhibits an inverse proportionality with grain size. This suggests that the grain size (3-10 mm, Fig. 2b in the manuscript) of the ice samples is coarse enough not to produce any measurable viscoelastic deformation under the testing conditions. It is also probable that for this grain size, there was not enough local concentration points to arrest the grain boundary sliding and drive the recoverable and reverse sliding. In addition, [5] discussed that regularly ordered and packed microstructures limit the amount of sliding and rearrangement and lead to less anelastic strain. The ice growth in the Aalto Ice tank was very controlled and resulted in homogeneous ice sheet.

Finally, the nonlinear mechanisms in the process zone possibly relieved the internal stresses that are needed to accommodate the grain boundary sliding and drive the recovery. This implies that any microstructural damage that occurred during loading manifested as permanent deformation at the end of the test.

Concerning the specimen size, our experiments used larger sizes than previous freshwater studies. Testing the effect of size requires a test program that use different specimen sizes while keeping all the other conditions fixed. All the above-mentioned factors may have contributed to the measured response. However, the question as to which factor influenced mostly the measured behavior is an another research question and requires more experiments. Testing the effect of each factor requires a test program that considers this factor while keeping all the other conditions fixed.

We thank the reviewer for his suggestion of testing smaller and colder samples to do a quick check. However, the authors believe that a quick check is not possible; the current tests were conducted under very controlled growth and testing conditions in the Aalto Ice tank. In addition, testing of smaller and colder samples cannot directly help the analysis in the current study; especially that several earlier studies used smaller and colder samples and reported significant viscoelasticity (cited in the manuscript).

3. Page 1, line 15 – I appreciate the authors for clarify that they interest is freshwater ice sheets and not sea ice floes or Antarctic/Greenland glaciers or ice shelves. While the motivation for the experimental study is clear now, please clarify what the motivation is for calibrating the Schapery model instead of a cohesive zone model.

Schapery's model was used because the model has been singularly powerful and successful for this type of creep/cyclic-recovery loading [1, 6]. Other analyses and approaches didn't do as well in modelling the load and unload periods. For instance, the experimental data by LeClair [6] was modelled by Schapery's model [6] and by a physically-based FE model [7]. While the physical model did a reasonable job of modelling the data, Schapery's straight-forward model did a better job.

In a recent publication by the same authors [8], a viscoelastic cohesive zone model was applied to model similar experiments of the same ice under monotonic loading. Wang et al. doubted the ability of the cohesive zone model to handle unloading [9]. They hinted at odd modelling results during the unloading phases. The back-calculated methodology of the cohesive model [10] is reliant on the monotonic growth of the process zone. This is problematic in the unloading phases where the cohesive model predicts a continuous increase in the process zone. In applying the cohesive zone model, the authors in [9] replaced the unloading phases by constant loading phases; assuming that the process zone stays constant during unloading.

In that sense, the ability of Schapery's model takes us a step further and allows the modelling of loading and unloading.

4. Page 6, line 189 – The authors referenced the work of Elices et al. (2002) that is entitled "Cohesive zone model: advantages, limitations, challenges." I am not sure how this paper is an appropriate citation for their argument about using indirect fitting methods. Please clarify and if you are using a specific argument/conclusion from Elices et al. (2002) put it in quotes.

Citing Elices et al. was added in the revised manuscript as a reply to reviewer 2 of the first review round. Elices et al. (2002) reviewed the cohesive zone model and included a discussion of the difficulties associated with direct experimental methods and the usage of indirect fitting methods instead. We cited their paper for the sole purpose of referring the reader to their discussion of parametric fitting. However, to avoid any confusion, the authors deleted the corresponding text from the revised manuscript.

5. Page 7, line 220 – Equation (11) is the main equation that relates CMOD with the applied load P. While the model agrees well with experimental data, wouldn't it be a better idea to calibrate a cohesive zone model and calibrate its parameters, so that it can be used for predicting ice fracture under realistic cases such as those mentioned in the first paragraph of the introduction..

See our answer to comment 3.

References

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