Interactive comment on
“Measurement of fracture toughness of an ice core from Antarctica”
by J.Christmann et al.

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general comments:
This paper presents the data from 108 four-point-bend fracture tests on machined sections of Antarctic ice cores. Careful measurements of the associated densities are reported. The fracture tests were conducted at one rate and one temperature.

specific comments:
Being very familiar with the fracture testing of ice, my impression is that the paper would benefit if it were quite focused. With regard to previous fracture testing of ice, just reference those who have tested antarctic ice.
The references (Goodman and Tabor (1978), Timco and Frederking (1982), Wei et al. (1991), Weber and Nixon (1996a), Weber and Nixon (1996b), Nixon and Schulson (1987), Nixon (1988) and Nixon and Schulson (1988)) in the introduction are given to provide the reader with the description to similar measure methodologies (three- and four-point loaded beams with a notch, as well as techniques for tensile bars with circulatory notches). However, the four-point bending technique was not yet applied to Antarctic ice samples. To the best knowledge of the authors the present investigation is the first attempt to apply this technique to Antarctic ice samples. Thus we prefer to keep the references.

Referencing Schulson and Duval (book) rather than Rist (1999) is not proper.
The revised version of the manuscript always includes the original reference of the data from Rist et al. (1999); see the fourth review comment of Referee #1.

You have failure times of 1 second, and you are doing an elastic analysis, so straying into time dependent discussions seems unwarranted.
In sections, the paper reads with an overview style, whereas I think that you should make it a more focused experimental report.
The aim of the description about fracture mechanics and the measurement technique makes the manuscript self-contained, since the authors are not

expecting that all readers are familiar with the different possibilities to measure fracture toughness of ice (an expert as you know these things). Furthermore, reviewer #1 requests more explanations.

How did you cut the cracks?

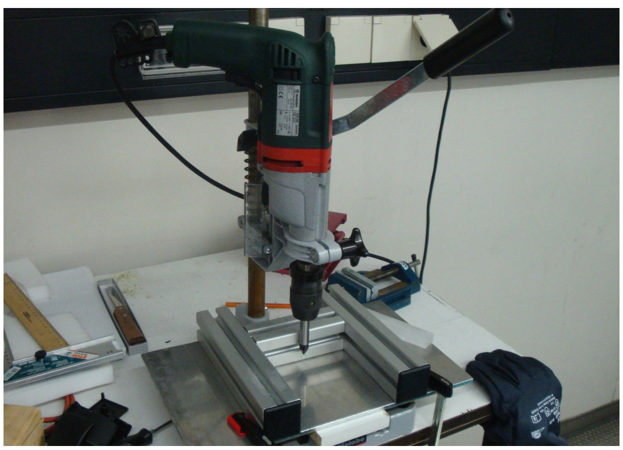
The sentence (p. 615, l. 25):

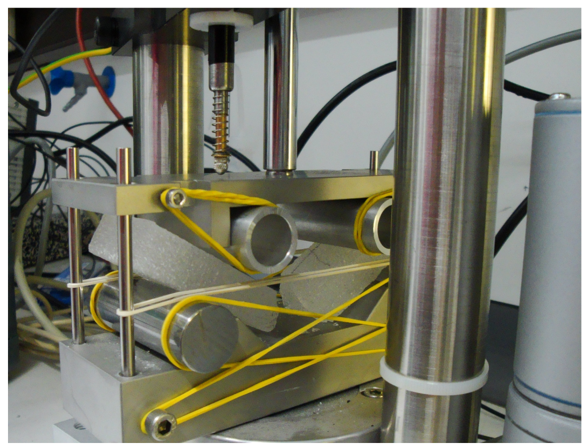
"Prior to testing, a notch was milled into each sample with a depth a~2.5mm and a notch radius r_a~100μm at -15°C."

is rewritten as:

"Prior to testing, a notch was milled into each sample with a custom-built milling machine to ensure repeatability. The milling procedure was performed at –15 °C and a notch of approximately 2.5 mm depth was cut into each sample. The final notch radius was approximately r_a~100μm, which was determined by the fixed radius of the cutting tool."

The following pictures show the milling procedure experimental setup by way of illustration:





How did you measure the notch radius?

The value r_a~0.1mm in the manuscript is determined from the geometry of the tool. In order to clarify this detail the following comment is added in the manuscript (p.615, l. 26):

"Following the milling procedure, the cutting tool was analyzed in a light microscope with 100x magnification and the radius of the tool tip was determined."

You could mention that Wei et al (1991) studied the influence of notch acuity.

Yes this is true and added (p. 618, l. 14):

"Wei et al (1991) studied the influence of crack (or notch) radii for fresh-water columnar ice produced with six different methods for single-edge-notched-bend specimens and analyzed the impact of notch acuity."

For further research, the measurements shown in this manuscript, should also investigate the fracture toughness values for other notch-tip geometries.

With a depth W of 14.30 mm, what lead you to choose a crack length "a" equal to 2.5 mm?
Given that the minimum grain size was 0.05 mm, and the maximum grain size was 4.48 mm, the crack face passed through a maximum of 5 grains, and a minimum of half a grain!
On average, the fabricated crack passed through slightly more than two grains.
What lead you choose B much larger than W?
"The width B of the sample is important to ensure that the crack tip is in a state of plane strain. This is proportional to the critical fracture toughness value and the inverse of the material's yield stress. In order to maximum the plane strain condition, within the possibilities afforded by the ice core geometry, B was taken to be larger than W to ensure that the crack face cut through minimum 6 grains.
As part of the widely accepted ASTM standards, the crack length-to-sample height ratio should ideally be between 0.25 and 0.65. Ratios outside of this window introduce very minor errors due, in part, to the proximity of the crack tip plastic zone to the sample edge, etc. In this study, however, due to the very low fracture toughness of ice, the crack was shortened slightly to increase the maximum force P_{max} required to cause failure. It was expected that a higher value would help reduce error or premature breakage during sample handling."

Could you have made W larger?
This is true. However, we were interested in performing as many fracture experiments as possible with the given ice core. This allowed us to measure 12 samples from the same cross-section with nearly the same density distribution.

Your equation for the four-point-bend stress-intensity-factor is unknown to me. Please cite a very specific reference.
This is the standard equation used in the ASTM Standards for the fracture toughness during 4 point bending experiments.

Often these expressions are accurate for specific outer span to depth ratios, very commonly 4 or 8. Your outer span to depth ratio is 7.2.
The ratio of the outer span S_o to depth W has to be adhered to for a certain interval in three-point-bending experiments. This is due to the fact that the crack is loaded by the changing shear force caused by the load directly above the crack. This ratio is not crucial in a four-point-bending experiment,

as the shear force between the inner two rollers vanishes and, therefore, the crack is loaded by a pure bending moment only.

You completed 108 fracture tests, with 17 breaking away from the notch. Of course this is a classic case of "notch insensitivity". Cases of notch insensitivity were discussed in 1991:
Dempsey, J.P., (1991) The fracture toughness of ice. Ice-Structure Interaction. IUTAM Proc.(ed. S. J. Jones, R. F. McKenna, J. Tillotson, and I. J. Jordaan) Springer-Verlag, Berlin Heidelberg, 109-145.
In this paper, the circumferentially-notched-round-bar (CNRB) fracture tests reported by Nixon (1988) and Nixon and Schulson (1988) were discussed (you cite these papers). Their tests were also notch insensitive.
It would be wise to complete a notch sensitivity study for your specific geometry to guide you as to the optimum crack length. Needless to say, one tries very hard to avoid notch insensitive tests.
There are two primary sensitivity issues during crack growth: (i) notch tip radius sensitivity and (ii) notch length sensitivity. Both affect the observed toughness value.

(i) the radius of the notch tip in relation to the grain size is an important parameter that affects the observed toughness value in polycrystalline materials. In the present case we have a radius-to-grain size ratio of approximately 11, which should be large enough to obtain repeatable results. In addition, Rist et al. (Fracture of Antarctic shelf ice, Journal of Geophysical Research, 107, 13 pp., 2002) has found that there is limited effect of the grain size on the fracture toughness of granular ice of the Ronne Ice Shelf at different depths.

(ii) During measurements, a somewhat shorter notch length was selected to increase the maximum force at breakage. In this way, some of the effects of premature breakage due to preloading or pre-test processes at the crack tip, such as plastic deformation, can be partially avoided. This, combined with the inherent distribution of intrinsic flaws in natural ice, led to the fracture not at the notch tip of 17% of samples. These samples were not used in calculations. For the other samples that broke at the notch tip, we have a defined sample geometry, notch radius and length, and mechanical loading and loading rate, which allows us to directly calculate the fracture toughness. Crack length-to-grain size sensitivity is a known issue in polycrystalline materials. The transition from single crystal fracture to polycrystalline fracture, governed by the microstructure, occurs over a range of crack length/grain size ratios and is material dependent. As a rule of thumb in ceramics a crack length/grain size ratio of ~10 is typically used. This is, however, in the present study not possible due to the limited dimensions of the available ice core and the average grain size (1.15mm).

In addition, there was unfortunately too little material available for a statistically significant notch sensitivity study, nor was this the primary goal of the investigation.

In Figure 6, is the Force the central load F, and is the displacement the load-point-displacement (LPD) "u"?

The caption of Fig. 6 is changed in the following sentence:

“Representative central load F and load-point-displacement data u as a ...”

Additionally, F and u are attached in the labels of the axes.

It would be very much more revealing to plot the force versus the displacement, and the displacement versus the time, along with the specified displacement versus time.

The force versus displacement is added additionally to Fig. 6 to clarify the loading situation to all readers.

Did you examine the crack paths, making thin sections to see whether the crack went through the air bubbles, through the grains or along the grain boundaries?

This is an interesting point, unfortunately due to time constraints in the lab we could not perform the analysis. In following investigations this will definitely be a point of consideration.