General Comments

This manuscript aims to address the question: "what is the tensile strength of ice?" using a unique set of stress data collected during the drainage of a glacier cavity. The authors utilize water pressure to directly calculate the force exerted on the glacier by slowly draining the cavity, mitigating some of the uncertainties in estimated stresses introduced by assumed rheological properties. The authors then use the finite element model Elmer/Ice to replicate the drainage with different rheological properties to see which model configuration best replicates observed stresses. The authors find that a non-linear viscous flow regime defined by n=3 best matches observations.

I found parts of the paper to be a little challenging to follow due to the structure it was presented in. Some of the readability issues are in part due to the overuse of passive voice in many sections. I have made more specific comments below on suggestions for improved readability.

Overall, I think this paper is an interesting concept with a unique dataset that approaches estimating tensile strength in a novel way, but could use further refinement in the parameters selected for the model and in the organization of the paper. My primary concern is in the choice to use a linear-viscous test case when such states have not been able to be reproduced in ice in the lab, and the absence of grain size dependent viscosity when n<3. I would also like more elaboration about the applicability of these results derived from a slow-flowing temperate glacier to fast-flowing, cold Antarctic ice. With these comments addressed, I think this paper will make an excellent contribution to the literature.

Specific Comments

Temperate glaciers, especially those with low stresses and strains, tend to have deformation dominated by grain boundary sliding (n=1.8). For deformation regimes defined by n<3, ice viscosity is non-linearly dependent on grain size, and the flow rate parameter has units of Pa^{-n} m^{-d} s^{-1} where d is the grain size exponent. In line 261, the units of the adjusted flow rate parameter for n=1 do not have a length component, suggesting the authors haven't included grain size dependence in the ice viscosity estimates. Goldsby and Kohlstedt (2001) have an equation for the flow law pre factor for n=1, but note that an n=1 flow regime has never been observed in laboratory experiments or natural terrestrial ice. Given the lack of observations of an n=1 flow regime in ice, I would recommend the authors replace the linear viscous test case with a model run with n=1.8 and a grain size dependent viscosity to make the test case more applicable to natural glacier systems. Goldsby and Kohlstedt's 2001 paper provides excellent estimates of A, n, and Q for various flow regimes, as well as modified Arrhenius relations that take into account grain size. Given the small strain rates described in the paper, I would expect grain boundary sliding to dominate over dislocation creep in the majority of the glacier, which may explain the overestimation of the subsidence rates in the n=3 regime. It also may be the case that during the drainage event, there is a shift from an n=1.8 to n=3-4 regime because of the increase in stress caused by loss of hydrostatic pressure. I wonder if there is a way to determine if this shift in n values occurs based on observed rates of subsidence over the cavity, or by crevasse opening rates? I would also be curious to see a prognostic model run with n=4, to complete the full range of non-linear viscous flow regimes for ice.

The majority of the tensile strength studies cited in this manuscript are derived from observations of cold ice, very fast moving ice, or both. I'd like to see some discussion about how tensile strength estimates might differ in temperate versus cold ice, and the applicability of the tensile strength estimates produced in this study to Greenland and Antarctica where the ice is flowing orders of magnitude faster and the deformation mechanism may be different. Currier and Schulson (1982) suggest tensile strength also has a grain size dependency, which may also affect the estimated tensile strength values of this study compared to estimates from Greenland or Antarctica.

Many sections of this paper alternate between passive (e.g. simulations were conducted, the data were extruded) and active voice (e.g. we conduct simulations, we extrude the data), making these sections challenging to follow. I would recommend the authors switch instances of passive voice into active voice. Section 2 is especially difficult to follow given the use of passive voice, as it is challenging to determine which actions were performed by the cited studies and which actions the authors took. Section 3 is also heavy on passive voice.

Lines 21-23: "In addition, crevasses are involved in two processes that control the rate at which ice sheets lose mass into the ocean: iceberg calving (Colgan et al., 2016) and accelerated flow due to the softening of shear margins (Borstad et al., 2016)." This line could use more citations for each case

Line 33-34: add Chudley et al., 2021 to citation list

Section 3:

- I would suggest a small restructuring of sections 3.2 and 3.3 to improve readability of the methods section. Rather than having the yield criteria in their own section breaking up the two sections on modeling, it may read smoother to split the last paragraph of section 3.3.3 into a new subsection solely about modeling damage, and move the descriptions of the yield criteria to the new subsection. So the flow of section 3 would be: model description —> diagnostic and prognostic —> implementing damage into model.
- Having the equations in the appendix made this section challenging to follow. I'd recommend integrating some of the key equations such as Glens law, the Arrhenius relation, and the equation used to calculate pressure from the water drainage into the main text

Section 3.2 intro: State a brief definition of equivalent stress

Line 195: State the sign convention for principal stresses (e.g. tension positive compression negative)

Equation 1: define what *Ice* σ_{III} is

Lines 281-282: "Water pressure is applied in the cavity, i.e. at nodes identified as being above the bedrock." Wording is confusing, as all nodes in the model domain are above the bedrock. Could be reworded as "Water pressure is applied in the cavity, i.e. at nodes on the basal boundary which are not in contact with the bedrock"

Section 4.4: The authors detail how they set up the prognostic model with the damage-dependent viscosity and talk about where damage develops with each given model, but do not show these results in data or figures. Is it possible to include a figure showing the evolution of D over time with each criterion?

The authors state that the maximum principal stress criterion fits the data best. From the provided figures, the maximum principal stress criterion and hayhurst criterion both look quite similar and both look like very good fits of the data. What factors influenced the authors to determine that the MPS criterion was a better fit than the hayhurst criterion?

Line 396-398: "Although the von Mises and Coulomb criteria should be disregarded on the basis…" I would recommend removing this whole sentence. Even if the results aren't as good of a fit as the others, the criteria can still provide useful information based on the assumptions they make about stress states. I would only include this bit if you weren't including all four criteria in your damage model, but since you're still using all four it seems unnecessary.

Line 416: "In contrast, peaks of $\sigma_{eq,vM}$ exceeding 200 kPa,…" I'm confused by the wording of the start of the sentence. Could it be reworded for clarity?

Line 470: "... it challenges findings based on glacier-scale in situ and remote sensing observations" These results fall squarely within the range of tensile stresses proposed by Vaughan. This would also be a part of the manuscript where I'd be interested to see some more discussion of how applicable these results are to the studies mentioned, which derive their tensile strength estimates from fast-flowing, cold ice.

Line 596-597: "we assume that damaged ice largely remains in regions where damage was initially created." It is correct that the ice remains in regions where the damage was initially created, but the stress state around them changes as the cavity fills and drains. The cavity refilling especially could create stress states that enable crevasse healing, as was observed with the stake measurements at crevasse tips which measured a closing rate of 5 mm/day. I agree that modeling crevasse healing is difficult given our current understanding of fracture mechanics and is outside the scope of this work, but this part of the reasoning should be reworded.

Figure 9: The caption states that pressure is defined as positive in compression and negative in tension, "as is standard in the glaciological literature". Pressure is defined by the principal stresses, and the standard sign convention within glaciology is that positive stresses are tensile and negative are compressive.

Technical Corrections

Equation 4: σ_I should be replaced with $\sigma_{eq,mps}$
Line 82: change "on the field" to "in the field"
Line 136: change "criterion" to "criteria"
Line 151: change "framework" to "frameworks"
Line 188: change "cold ice" to "colder ice" since cold ice is often interpreted as ice colder than -10°C

Line 215: change “highest” to “largest”, “eigen value” to “eigenvalue”
Line 328: change “slightly more (resp. slightly less)” to “slightly large (resp. slightly smaller)”
Line 379-380: “Only the crevasse at the upstream end of the AA’ profile seem to occur…” Mismatched tense. Either “crevasse” needs to be plural or “seem” changed to “seems”

Miscellaneous figure notes:

- The magenta lines denoting unrelated crevasses are sometimes hard to see on the chosen color map. I’d recommend changing them to a color that has more contrast, or removing them from the figures entirely after introducing them in the first figure.
- Add arrows in the figures that denote the direction of ice flow
- Figure 4: if using the same color map for all displacement directions, keep color bar limits consistent across x, y, and z domains

References

Goldsby, D. L., and D. L. Kohlstedt. “Superplastic Deformation of Ice: Experimental Observations.” *Journal of Geophysical Research: Solid Earth* 106, no. B6 (2001): 11017–30. https://doi.org/10.1029/2000JB900336.

Currier, J. H., and E. M. Schulson. “The Tensile Strength of Ice as a Function of Grain Size.” *Acta Metallurgica* 30, no. 8 (August 1, 1982): 1511–14. https://doi.org/10.1016/0001-6160(82)90171-7.