Correspondence

On Duddu and Waisman (2012, 2013) concerning continuum damage mechanics applied to crevassing and iceberg calving

This correspondence relates to two papers by Duddu and Waisman (2012, 2013), recently published in *Mechanics of Materials* and *Computational Mechanics*, respectively. We thought it pertinent to comment on the ice rheology approach considered in their damage model, and its application to the prediction of crevasse opening and iceberg calving. The *Journal of Glaciology* appeared to be the appropriate journal for this purpose, in order to interact with as many potential users of this model as possible.

Duddu and Waisman (2012, 2013) presented a new damage model, with the aim of applying it to the formation of glacier crevasses and the calving of icebergs. Duddu and Waisman (2012) estimated the parameters entering the damage model using published data from laboratory mechanical tests. Duddu and Waisman (2013) presented the concepts of the model, as well as some numerical aspects. The model itself appears to be very sophisticated, with interesting and innovative aspects such as a nonlocal formulation which avoids mesh-size dependency of the results. However, the ice rheology specificities are not accurately considered due to a misunderstanding of the physical mechanisms in play. We have two main criticisms of the way the model has been formulated and calibrated, which are significant enough to suggest that caution is needed in adopting the model for use in its current form.

First, the model relies on the formalism of Murakami (1983), which was initially developed to account for the ductile failure induced by the nucleation and growth of cavities. Adopting this formalism renders the fundamental basis of the proposed damage model incompatible with the negligible contribution of diffusion creep to ice deformation. Indeed, ductile failure requires strong intra- or intergranular diffusion while diffusion in ice is low (Duval and others, 1983). Damage in ice occurs through the nucleation of brittle microcracks, arising from stress concentrations created by elastic mismatch between grains, dislocation pile-up formation and/or grain-boundary sliding (Weiss and others, 1996; Frost, 2001). Following the formalism of Murakami (1983), the damage is initiated using a strain criterion (equation (23) of Duddu and Waisman, 2012). With such a formulation, as soon as the deformation reaches the strain threshold $\varepsilon_{\rm th}$, the ice damages continuously whatever the applied stress. Such a strain threshold is unphysical: ice can deform up to very large values without damage if the strain rate is sufficiently low. As a matter of fact, a critical strain rate can instead define, macroscopically, the transition from a purely ductile behaviour to a more brittle behaviour involving damage (e.g. Schulson and Duval, 2009). Hence, adopting $\varepsilon_{\rm th} = 0.8\%$ is not appropriate for the many places in ice sheets and glaciers where tensile stress remains too small to initiate any damage, whatever the deformation level (e.g. Budd and Jacka, 1989).

Second, the model is calibrated using the experimental creep tests of Mellor and Cole (1982) for compression, of Mahrenholtz and Wu (1992) for tension and of Jacka (1984) for temperature dependency. For these creep tests, damage may only explain a small part of the total deformation (Mellor and Cole, 1982) or even not have occurred during the tests (Jacka, 1984). The underlying hypothesis in Duddu and Waisman (2012) is that all the tertiary creep deformation is due to damage, neglecting other softening processes, such as dynamic recrystallization, associated with the nucleation of new grains and grain boundary migration, which is very active in glaciers and ice sheets (e.g. Schulson and Duval, 2009). In Jacka's (1984) experiments, the increase in strain rate during tertiary creep is clearly associated with dynamic recrystallization alone, applied compression stresses being much lower than those required to form microcracks (Schulson and Duval, 2009). To discriminate the effects of damage and other processes on tertiary creep, sequential tests must be performed (e.g. Meyssonnier and Duval, 1989; Weiss, 1999). Ice is predamaged up to a certain level during the first sequence, either under strain-rate control or creep (constant stress). The creep response of the damaged samples is then analysed under low applied stress (low enough to avoid additional damage). These studies have shown that viscous strain is indeed enhanced by damage, whereas delayed elastic strain is not, contrary to the postulate in Duddu and Waisman (2012, 2013). Beyond these problems in identifying appropriate damage models for ice, we also stress that the automatic application of such models, inspired by processes occurring at the microscale, to geophysical situations must be treated with caution. Indeed, little is known so far about the role of microscopic damage in crevasse propagation or iceberg calving. While continuous damage models may be promising tools with which to simulate crevassing, the construction and calibration of such models must be based on a comparison with large-scale (field or remote-sensing) measurements (e.g. Pralong and Funk, 2005).

For the above reasons, we consider that this model is not, at the present stage, adapted to reproduce the rheological behaviour of ice for the conditions prevailing in glaciers and ice sheets, and so cannot be relied on to accurately predict crevasse opening and iceberg calving.

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