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Interactive comment on "Combining damage and fracture mechanics to model calving" *by* J. Krug et al.

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This is an interesting and important paper that develops the concept of crevasse-depth calving models in promising new directions. In particular, the combination of a damage evolution model and LEFM fracture propagation is a significant innovation, which may improve the ability of crevasse-depth models to represent some kinds of calving event.

My comments here do not address the details of damage evolution or LEFM modeling (which have been covered in Chris Borstad's thorough review), but focus on the general model structure, its relationship to other calving formulations, and the application of the model to Helheim glacier.

First, in the introductory section referencing of earlier work is very careless, and sug-

gests a very casual approach to the literature. Proper acknowledgement needs to be made of how the present model builds on previous work, especially the crevasse depth model developed by Benn (2007a, b) and Nick (2010). Indeed, the present model is not so much a 'new framework', as a refinement of the existing crevasse-depth model framework, using more sophisticated treatments of damage and fracture.

Second, it is arguable whether the new model has been 'validated' by the Helheim model exercise, as against 'tuned'. As the authors are no doubt aware, tuning of model parameters to fit output to observations does not mean that the model correctly represents reality. I believe that the current paper represents a significant conceptual advance in how calving processes might be represented in continuum models, but it has not been demonstrated that the model will necessarily perform better than simpler formulations. Formal model inter-comparisons will be required to test this.

Third, as regards modelling calving at Helheim glacier, the omission of basal crevasses in the new model is a major shortcoming. Observations by Murray et al. (2013) demonstrate that surface crevassing does not contribute significantly to large calving events at Helheim, but basal crevasses do. The model used by Nick (2013) to model calving losses at Helheim includes basal crevassing, and is more likely to capture the actual processes of mass loss than a model based on surface crevasse propagation alone. This means that in its present form the damage/LEFM almost certainly misrepresents calving at Helheim Glacier

Some detailed comments:

p. 1111: modify wording in the abstract on line 2 ('new calving modeling framework' to 'new development of crevasse-depth models') and line 8 ('validated' to 'tuned').

p. 1113, line 6. The referencing here is very inaccurate. The wording appears to imply that Nye proposed a calving criterion, not just a simple formula for the penetration of crevasses. Instead, it should be stated that the crevasse depth calving criterion was proposed by Benn (2007a, b), and implemented in a higher-order flow model by Nick et

al. (2010). Mottram and Benn (2009) did not 'use' the calving criterion, but compared predictions of the Nye and LEFM models with field data. Their study found that the Nye model performed almost as well as the LEFM approach, and had the advantage that crevasse spacing did not need to be known. The choice of the Nye formula in the model of Nick (2010) was therefore based on a rational argument backed up with field data. At present, there is no means of telling if the new approach is better or not.

p. 1113, lines 12-15. It is true that the Nye crevasse depth formula does not incorporate stress concentration effects, but as pointed out by Benn (2007b), stress concentration effects are relatively small in fields of closely-spaced crevasses. The statement that the Benn-Nick model does not account for 'the crevasse depth' is wrong, as calculation of crevasse depths is at the core of the model. The statement about the 'ice discharge' is also incorrect. The approximations used in the Benn model may result in some error in the position of the margin, but the predicted discharge mostly reflects basal sliding functions, which are not at issue here. In addition, as pointed out in Borstad's review, it is by no means clear that the concept of a lone crevasse running ahead of all others is an accurate representation of reality. So it remains to be demonstrated that the new approach is superior in practice to models incorporating the Nye function.

P. 1113, line 19: the Åstrom model can simulate both viscous and brittle behaviour, so it is wrong to say that its 'non-continuous approach' is a limitation. Its main limitation at present is that it is very computationally demanding, but in concept it is actually better for all types of glacier modeling than continuum models.

At present, the paper is rather dismissive of previous approaches, but in fact it borrows heavily from earlier work and it should be clearly acknowledged that the authors' model is closely similar in concept and structure to the existing crevasse-depth calving model. The new paper develops the concept to incorporate more detailed formulations of damage and fracture propagation. This is a significant development of the concept, although it remains to be seen whether the modifications result in improved model performance.

p. 1113, line 20: 'apparition' in English usually means the appearance of a ghost. 'development' would be a better word.

p. 1113, line 26: Van der Veen's papers did not apply LEFM to calving, but to analyze the penetration of surface and bottom crevasses. Also change 'employed to described' to 'employed to describe'

p. 1114, line 3: The IGS is a 'large glaciological body'. Better to say 'large ice masses'

p. 1121, line 18: 'pretty well' is a very vague! And of course, the Nye model performed almost as well.

p. 1123, line 27. 'we do consider' should be 'we do not consider'. As noted above, this is a major shortcoming when it comes to modeling Helheim glacier.

p. 1124, lines 4-5: this is inaccurate. For a fixed small (several m) water depth, there will be a corresponding finite crevasse depth. Full depth crevasse penetration requires continuous input of water to keep the crevasse nearly full.

P. 1125, line 7: It is now possible to acknowledge the source of the re-meshing scheme - which was vital to the simulations - by referencing Todd and Christoffersen (2014). This should be done as the brief statement in the acknowledgements does not communicate to the reader the importance of this input.

p. 1125, line 22: 'validate' should be 'test' or 'evaluate'.

p. 1131, line 6: the glacier studied by Mottram and Benn is in fact in Iceland, not Svalbard, and calves into a lagoon, not the sea. Did the authors actually consult this paper? But in any case, the crevasse depths observed at their site, where strain rates are quite low, do not provide useful validation of the modeled thickness of damaged ice on Helheim.

p. 1131, line 27: 'At last' should be 'Finally'

p. 1132, last paragraph: the arguments here are rather weak. Given that: a) the

simulations on which this statement are based are an arbitrarily chosen subset of an ensemble that exhibits a huge range in behaviour, b) the simulations do not replicate the observed oscillations of the front, and c) a major process (basal crevassing) is missing, there are really no grounds for making any claim about the causes of the observed glacier behaviour.

p. 1133, lines 19 and 22: 'reliable' should be 'reasonable' in both cases.

Additional references:

Benn, D.I., Hulton, N.R.J. and Mottram, R.H. 2007a. 'Calving laws', 'sliding laws' and the stability of tidewater glaciers. Annals of Glaciology 46, 123-130.

Murray, T., Rutt, I.C., O'Farrell, T., Edwards, S., Selmes, N., Martin, I., James, T., Aspey, R., Bevan, S., Loskot, P. and Bauge, T. 2013. High-resolution monitoring of glacier dynamics during calving events at Helheim Glacier, southeast Greenland. AGU Fall Meeting abstract, C21A-0614.

Todd, J. and Christoffersen, P. 2014 Are seasonal calving dynamics forced by buttressing from ice mélange or undercutting by melting? Outcomes from Full Stokes simulations of Store Gletscher, West Greenland. The Cryosphere Discuss.

Interactive comment on The Cryosphere Discuss., 8, 1631, 2014.