Reply to Referee #1

We thank the reviewer for the insightful and constructive comments. In the following, we reply point by point on the reviewer's comments. They are shown in italic, our replies are in plain red and manuscript modification that we will make are in blue.

The manuscript titled "Micromechanical modeling of snow failure" by Bobillier et al. reports the setup and the results of numerical DEM models aiming at studying the failure of weak snow layers. The paper is based on the fact that complex and detailed numerical models are extremely time-consuming. On the contrary, it is possible to build simplified models that are able to catch the main characteristics of the investigated material. In the proposed approach, such models are constituted by different layers of spherical particles. The approach is original and interesting results can be obtained from such numerical setup. The authors "tuned" particle properties by simulating real experiments. This approach is commonly used in other engineering disciplines.

In addition, they predicted the behavior of such complex material under particular stress conditions, say, pure traction, for which no experimental pieces of evidence are present. Referring to this last point, the possibility of "extrapolating" the behavior to something that is hard to replicate in a laboratory has to be further discussed in detail and the limitation of the approach must be clearly stated.

In addition, there are some points that are not clear and must be detailed.

We will amend our manuscript to clarify some parts that were unclear to the reviewer and more thoroughly discuss the limitations of the model and how the results can be generalized.

1 *P.2, L.6: to which properties do the authors refer with "and possibly other ones"?*
We will add examples of other snow properties that can be related to the dynamics of crack propagation such as slab porosity, weak layer failure envelope, weak layer elasticity, microstructure:

However, no theoretical framework exists that describes how these mechanical properties and possibly other ones such as weak layer failure envelope, weak layer elasticity or microstructure relate to the dynamics of crack propagation at the slope scale.

2 *Referring to the contact model (P.3), it is not clear when the contacts are activated and when not. In other words, it is possible that new contacts form during the test, or not?*
Thank you for this remark. Once a bond breaks, only particle frictional contact occurs and no new bonds are created (i.e no sintering occurs). This assumption is motivated by the fact that

the strain rate is large and the time scale is seconds during a PST experiment. We will explicitly mention that we do not expect sintering.

In addition, a more detailed description of the contact model will be given in the manuscript with the following figures (a, b).

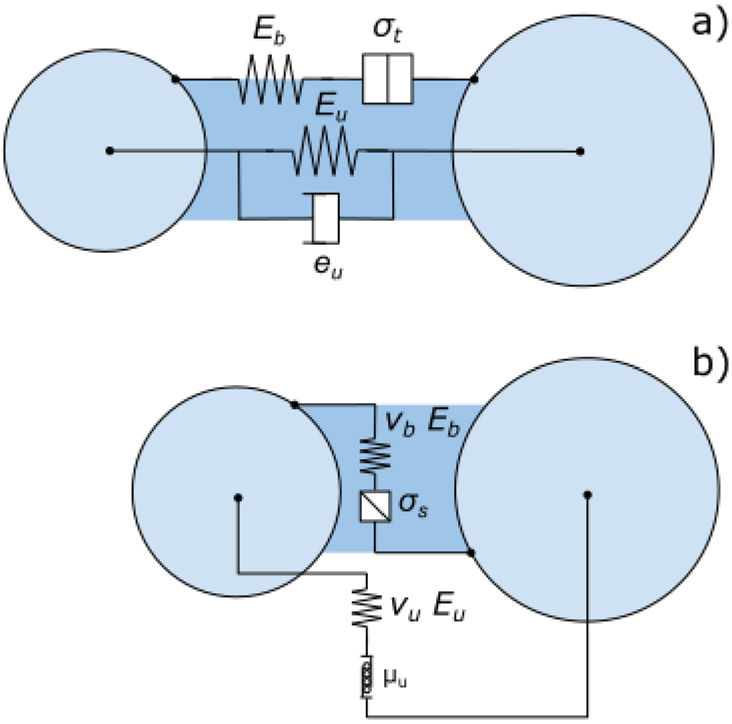

Figure a: Representation of the PFC parallel bond model (PBM) used in the simulations. a) Normal mechanical parameter bond and unbonded, where E_b represents the bond elastic modulus, σ_t the tensile strength, E_u the contact elastic modulus and e_u the restitution coefficient. b) Shear mechanical parameter bond and unbonded, where E_b represents the bond elastic modulus, σ_s the shear strength, E_u the contact elastic modulus, υ_b the bond Poisson's ratio and μ_u the friction coefficient.

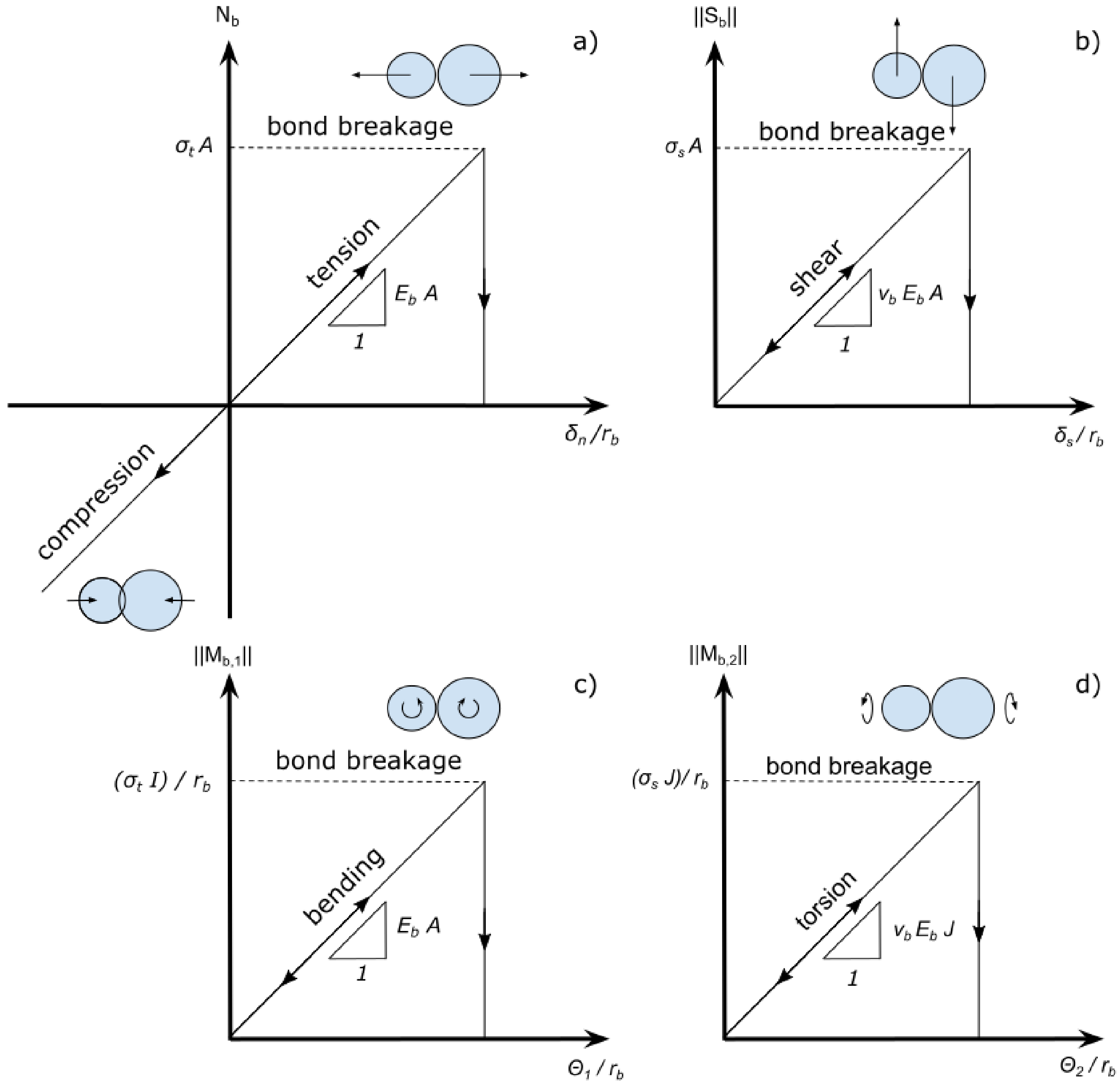

Figure b: Representation of the bonded behavior of PBM used in the simulations. (a) Bond normal force N_b as a function of the normal interpenetration δ_n scaled by the bond radius r_b. (b) Bond shear force $\|S_b\|$ as a function of tangential interpenetration δ_s scaled by the bond radius r_b. (c) Bond-bending moment $\|M_{b,1}\|$ as a function of bending rotation θ_1 scaled by the bond radius r_b. (d) Torsion moment $\|M_{b,2}\|$ as a function of twist rotation θ_2 scaled by the bond radius r_b.

3 *P.3 L.15: scaling the size of the layer through homothetic transformation does allow to state that the mechanical properties are conserved? short but detailed study on scaling laws would be appreciated.*

Performing simulations of weak layers of different thickness generated through homothetic transformation shows the same mechanical results (see figures c, d). The bond strength and elastic modulus are scaled such that the macroscopic mechanical behavior becomes almost exactly the same for different values of weak layer thickness (see figures c, d). This will be clarified in a section that will be added to the supplementary material. The equation to characterize macroscopic properties can be written as:

$$E_{wl\,macro} = (\beta_0 + \beta_1\, E_{particle}) / \left(\frac{h_{wl\,ref}}{h_{wl}}\right)$$

$$\sigma^{th}_{wl\,macro} = (\gamma_0 + \gamma_1\, \sigma^{th}_{bond}) / \left(\frac{h_{wl\,ref}}{h_{wl}}\right)$$

Where $h_{wl\,ref} = 3cm$ and h_{wl} correspond to the new weak layer thickness.

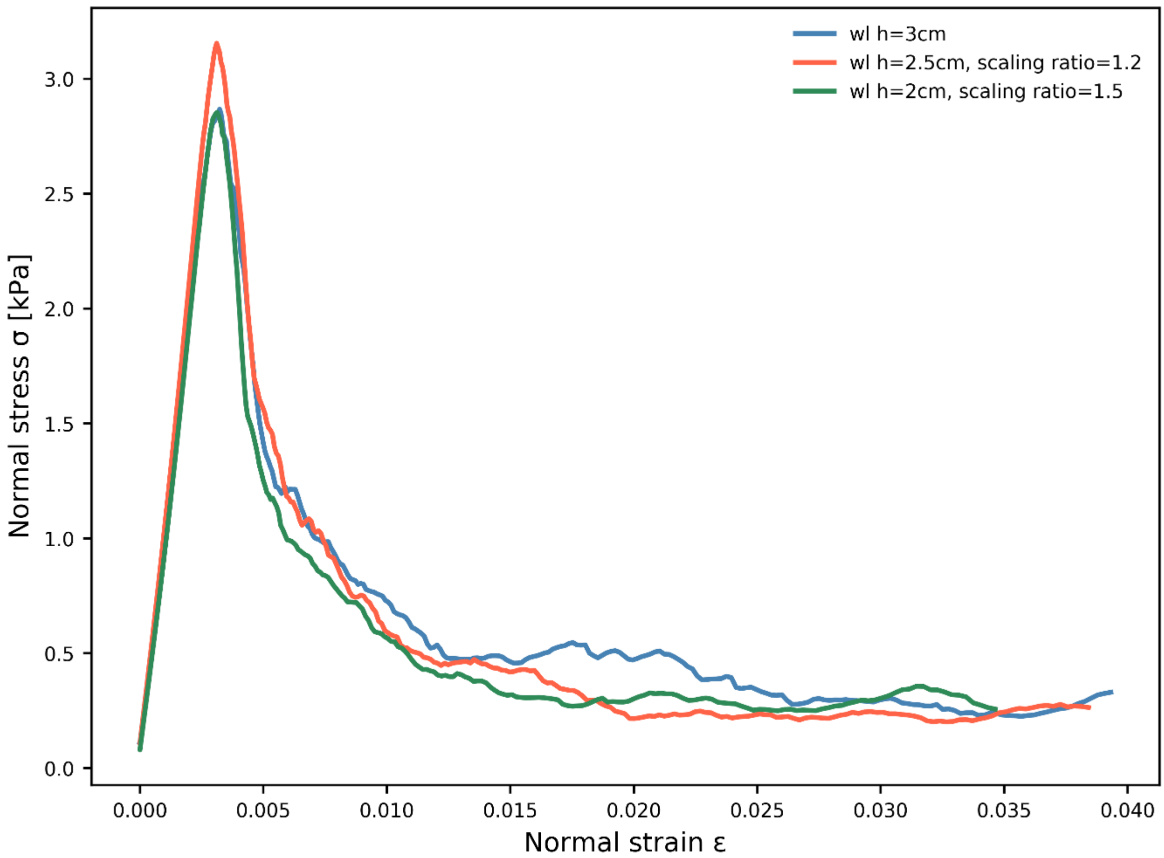

Figure c: Stress-strain curves for weak layers of different thickness (colors) under load-controlled compression. The blue line shows the reference weak layer with a thickness of 3 cm.

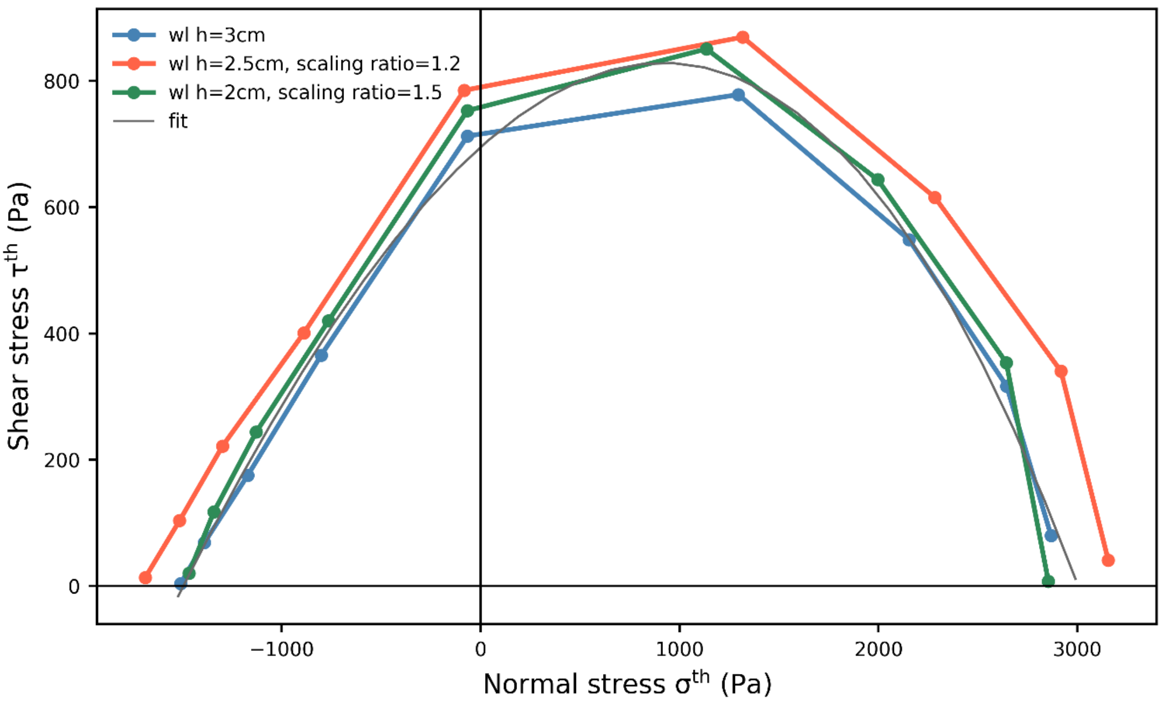

Figure d: Failure envelopes for weak layers with different thicknesses (colors) and fits based on equation (9).

4 *P.3 L.25: a lot of attention is given to the density. Why? It seems that the results are not density-dependent*

In a real snowpack, snow density is a very important parameter, as many mechanical properties scale with density (e.g. Shapiro et al. 1997, van Herwijnen et al., 2016). Snow properties such as $\sigma^{th}_{slab\ macro}$ or $E_{slab\ macro}$ are thus often defined as function of mean slab density. However, slab density directly relates to the load on the weak layer, which influences crack propagation propensity and thus slab avalanche release. The density and the thickness of the slab will determine the load. If the stress state given by this load is outside of the failure envelope of the weak layer, failure can occur. Here, a lot of attention was given to the evaluation of the failure envelope, which defines the critical load. In our simulations, as you correctly mention, weak layer density does not play a crucial role.

5 *P.4 L.5: the authors assumed that bond strength and particle elastic modulus are independent. Is this consideration supported by data, observations, previous researches, or is it a hypothesis?*

In some materials strength and elastic modulus are related, while in other materials both properties are not related. For snow, it remains unclear if those two properties are related. Our goal was to independently control both parameters in order to have a precise control on the macroscopic elastic modulus and macroscopic strength of the snow

6 *P.4 L.20: it is not clear the test setup. It seems that the density of the actuator layer is rapidly increased to simulate a normal vertical pressure. Why we should expect shear strains into the weak layer?*

We will improve Figure 1 in the manuscript to more clearly illustrate the test setup (see figure e).

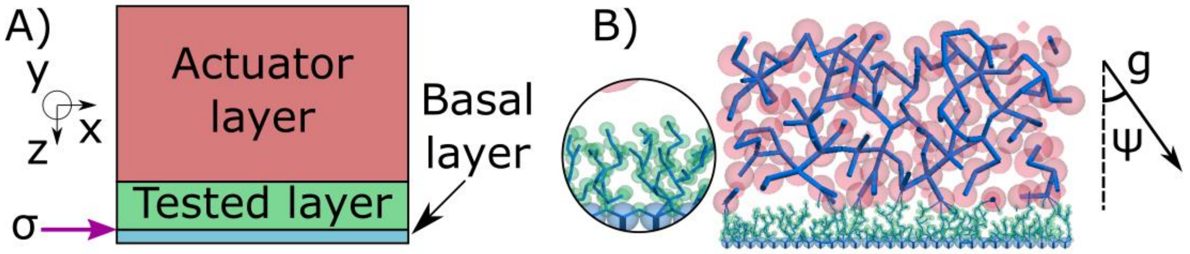

Figure e: A) Coordinate system and diagram of the setup consisting of the basal layer (blue), the tested layer, in this case a weak layer, (green) and the actuator layer (red). The violet arrow points to the interface between basal and tested layer where the stress is measured. B) slice of a generated system consisting of a slab layer (large red particles) and a porous weak layer (small green particles). A zoom of the weak layer is shown in the circle. The lines represent bonds between particles. Applied gravity is defined on the right where ψ is the loading angle.

The stress on the weak layer is increased by increasing the density of the actuator layer. By changing the gravity angle, mixed-mode loading is simulated. Through this change in the angle of gravity, the tested layer is under both shear and normal stresses. This will be clarified in the revised manuscript.

7 *Referring to the characterization of macroscopic properties, the authors performed a Latin hypercube sampling on the values of the elastic modulus of the particle and the strength of the bond and obtained the macro-properties of the slab. Many issues arise: why in Figure 2a only 9 simulation points appear, while the authors have performed 100 simulations? Are those points related to a particular value of σ_{bond}^{th}? Are the values of coefficients β_0: feasible/realistic? Please add the units of measure to β_0 and γ_0.*

Thanks for this remark. We performed 9 x 9 simulations (81 simulations) for the weak layer (Fig. 3) and 10 x 10, 100 simulations for the slab layer (Fig. 2). This will be clarified. In Figure 2a, each blue dot represents the mean value of the macroscopic elastic modulus for a fixed E_{particle} and ten σ_{bond}^{th} values (as explained in the caption). A qualitative comparison with data presented by Shapiro et al. (1997) suggests that the values we used are realistic for slab and weak layers. The goal of the layer characterization is to show that the macroscopic properties (E_{macro}, σ_{macro}^{th}) can be controlled in a range that is typical for snow. The units of β_0 and γ_0 are Pascal (Pa), which we will add in the manuscript.

8 *Referring to the mechanical behavior of layers, it is necessary to define what a failure is. Failure in tension is different from failure in compression or in shear. Referring, for example, to tension tests, how such tests were performed? Have the results of tension tests been compared with tests on real snow? In general, synthetic models are able to "interpolate" rather than "extrapolate".*

In our simulations, mixed-mode loading is applied by changing the angle of gravity. We agree that this was not clearly stated. We will revise the manuscript to clarify this point. Hence, the identification or definition of failure does not depend on the mode of loading. Failure is simply identified as the point of maximum shear or normal stress. This point precedes the onset of softening (see Figure below). We will clarify this as well in the revised manuscript.

Tension tests were simulated with a negative gravity ($\psi = 180°$). For tension test results we are in the upper range of the tensile strength values reported by Sigrist (2006). However, we can calibrate our microscopic properties to get the macroscopic properties we want.

9 *P.8 L.11: Which is the meaning of "shear acceleration"?*

Thanks for this remark. We agree that the term shear acceleration was not very adequate and we will change it to "tangential acceleration" in the revised manuscript. This tangential acceleration is the 2^{nd} derivative of the tangential displacement.

10 *Referring to the failure envelope reported in Eqn. (9), what σ^{th} does represent? Can the failure envelope be used in a real snowpack on a real slope? In addressing this issue, the authors must consider the fact that their tests were performed in unconstrained lateral conditions, different from boundary conditions that can be observed in a continuous layered snowpack.*

Thank you very much for noticing this omission of defining σ^{th} and τ^{th}. σ^{th} represents the fitted normal strength and τ^{th} the fitted shear strength. This will be modified in the revised manuscript. Concerning the second aspect on the confinement and real slopes, we checked that unconfined and confined loading conditions yield the same results for weak layer behavior. This finding is due to the large porosity (80%) of the weak layer (see figure f). We will add this figure to the supplementary material.

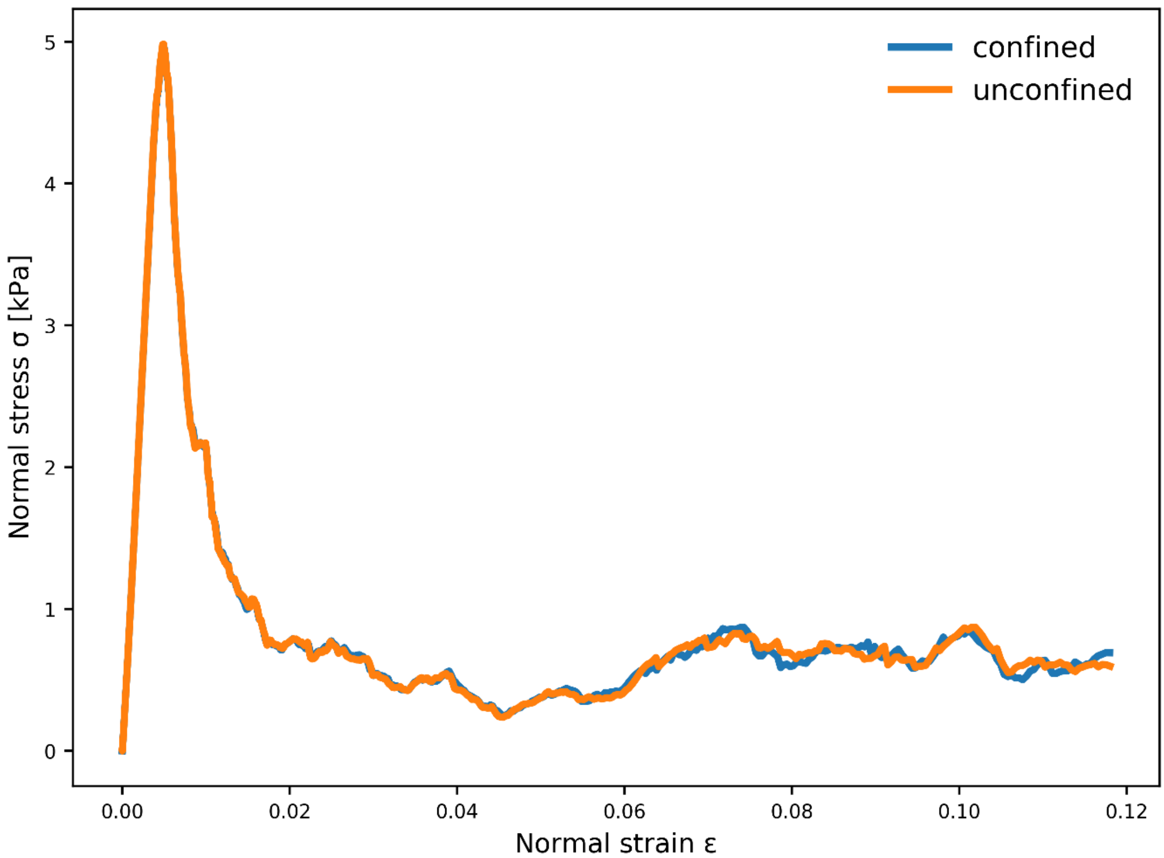

Figure f: Weak layer behavior under load-controlled compression ($E_{particle} = 1\ \mathrm{MPa}$ and $\sigma_{bond}^{th} = 5\ \mathrm{kPa}$). The blue line shows the normal stress during confined test and the orange line during unconfined test conditions.

11 As stated in the introduction, the failure of snow slabs depends on many parameters, such as the fracture energy. Have the authors considered this important parameter in their simulations?

In our simulations, the fracture energy is related to the area below the stress/strain curve in the softening region. This is a result and not an input of the simulation. This fracture energy depends on the weak layer microstructure, the elastic modulus and the strength. We analyzed the results with regard to the softening ratio instead of the fracture energy which shows that the maximum acceleration and the percentage of broken bond at the end of the softening phase is driven by the softening ratio. To answer your question more specifically, the fracture energy is included in our model but we preferred to analyze our results in terms of strength of materials rather than in terms of fracture mechanics. Gaume et al. (2014) showed that the two approaches can be related to each other.

12 *In granular materials, failure mechanisms presuppose the formation and the subsequent destruction of force chains. Evidence of such behavior has been observed on real snow tests (De Biagi et al., European J. of Mech. - A/Solids, 74, 26-33, 2019). The observation of such mechanisms in simplified numerical models support the conclusions. Have the authors noted such behaviors in their tests?*

For computational reasons, the weak layer was modeled with around 10 vertical particles, which did not allow us to observe a clear strain localization within the weak layer. However, given for the large amount of softening we observe after failure, we expect that higher weak layer resolution would allow to observe this feature.

The figure below shows the stress–strain curve shortly before and after the peak stress; some non-linear behavior appears before failure (figure g: a.1). Following the bond-breaking position before failure (figure h) confirms the presence of initial crack formation. Our simplified model does not explicitly show crack growing by clustering; this behavior could be investigated for by increasing the number of particles in the weak layer, which will increase the vertical resolution.

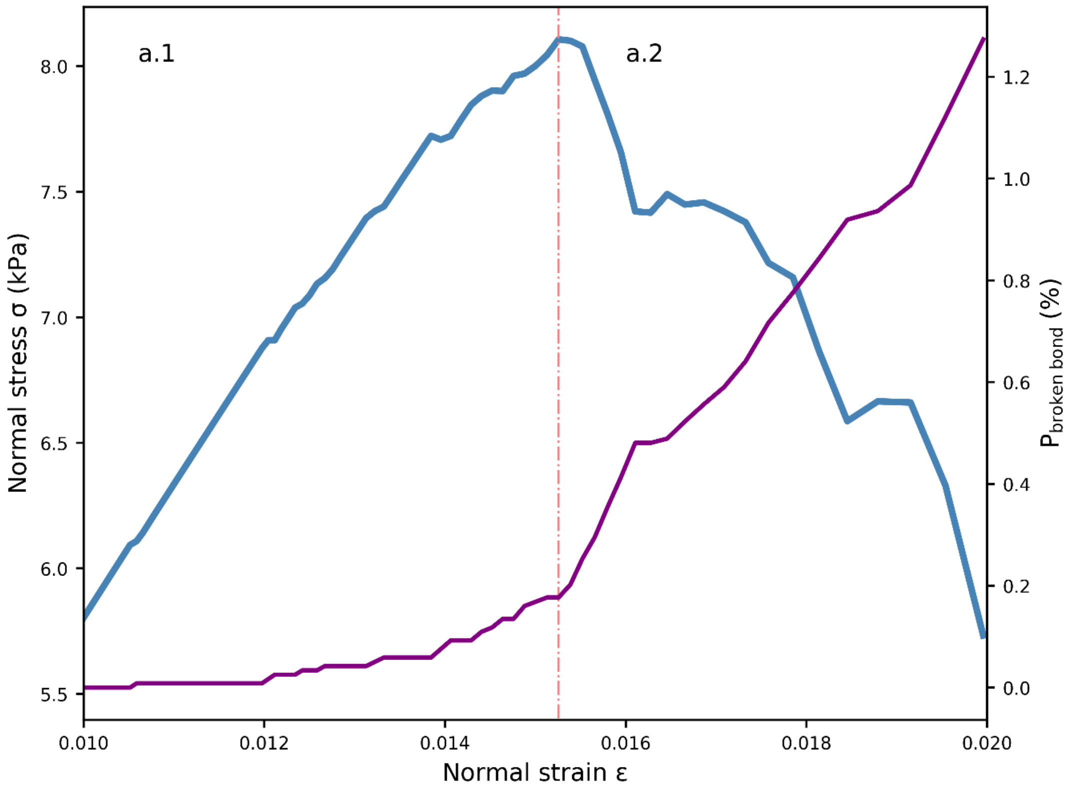

Figure g: Zoom of the weak layer behavior under load-controlled compression around sample failure ($E_{particle} = 30MPa$ and $\sigma_{bond}^{th} = 500kPa$). The blue line shows the normal stress before (a.1) and after (a.2) failure of the weak layer. The violet line corresponds to the proportion of broken bonds (%).

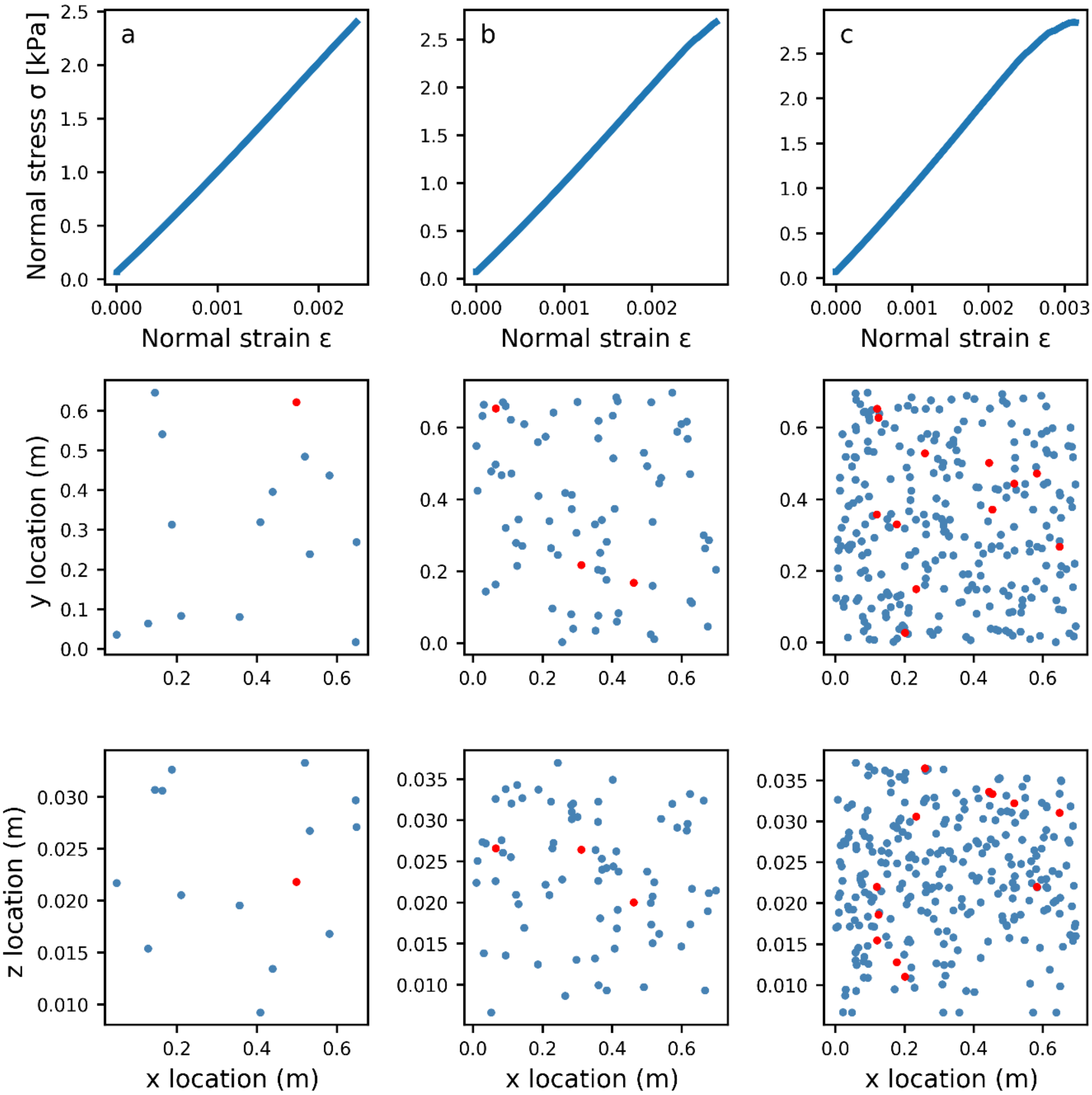

Figure h: Pre-failure crack formation. Plots (top to bottom) represent stress–strain curves, top views of the position of broken/breaking bonds in the weak layer and a side view of the position of broken/breaking bonds. Red dots represent breaking bonds and blue dots broken bonds. a. weak layer behavior at the time where the stress-strain non-linearity start (shortly before failure). b. weak layer behavior during stress-strain non-linearity. c. weak layer behavior immediately before the failure. Bonds break in spatially random manner (no localization observed)

References

Gaume, J., Schweizer, J., van Herwijnen, A., Chambon, G., Reuter, B., Eckert, N., and Naaim, M.: Evaluation of slope stability with respect to snowpack spatial variability, J. Geophys. Res., 119, 1783-1799, https://doi.org/10.1002/2014JF00319, 2014.

Shapiro, L. H., Johnson, J. B., Sturm, M., and Blaisdell, G. L.: Snow mechanics - Review of the state of knowledge and applications, US Army Cold Regions Research and Engineering Laboratory, Hanover, N.H., U.S.A.CRREL Report 97-3, 43, 1997.

Sigrist, C.: Measurement of fracture mechanical properties of snow and application to dry snow slab avalanche release, Department of Mechanical and Process Engineering, ETH Zurich, Zurich, Switzerland, 139 pp., 2006.