INVESTIGATION OF THE INTERPLAY BETWEEN SHEAR FAILURE AND NORMAL COLLAPSE OF WEAK LAYERS USING MICROSTRUCTURE-BASED MECHANICAL SIMULATIONS

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ABSTRACT: Weak layers of snow are thin layers of low density and cohesion that consist of a complex network of sintered ice grains. These layers are very fragile and their failure is considered to be the primary cause of dry slab snow avalanche release. This study reports on the results of modelling the mechanical response of these weak snow layers with discrete element (DEM) simulations, using X-ray microtomographic images of real snow samples as input data. An original method for approximating arbitrary grain shapes in DEM was developed that enabled us to accurately capture the effect of snow microstructure on the mechanical behaviour of varying snow types, including weak snow layers. Three samples of different snow types have been subjected to simple shear simulations with varying normal pressure and a qualitatively similar result was obtained for all three samples. The simulation results permitted us to study the failure as well as post-peak strain softening and residual stress in snow. Failure envelopes of different snow types are presented and the effect of the microstructure on the failure envelope characteristics is analyzed. A detailed investigation of the interplay between shear failure and collapse is conducted and put into perspective by the damage that progressively propagates through the specimen.

Keywords: Weak snow layer failure, normal collapse in shear, slab avalanche release

1. INTRODUCTION

The main trigger of dry snow slab avalanches is failure in a weak layer underlying a cohesive slab of snow (Schweizer et al. (2003)). This makes the thorough understanding of weak layer mechanics, especially under mixed-mode shear and normal loading, a crucial ingredient of snow avalanche release modelling. In spite of its importance, the mechanism of weak layer failure has long eluded the snow avalanche research community.

The elastic phase of weak snow layer mechanical response to external loading is relatively well understood as it has been successfully modelled by applying FEM calculations directly to X-ray tomographical images of snow microstructure (Köchle and Schneebeli (2014); Srivastava et al. (2016)). It has been shown that density as well as snow structural anisotropy have a decisive effect on the snow stiffness in the elastic phase. The subsequent failure under mixed-mode loading has been studied by in-situ (Chandel et al. (2014)) as well as laboratory (Reiweger et al. (2015)) experiments. It has been shown that weak layers feature closed failure envelopes, indicating that weak layers can fail under pure normal loading. The failure envelopes have been shown to resemble Mohr-Coulomb criterion with a cap, but the authors have not explored the relation between failure envelopes and the microstructure. The post-failure response of weak layers to mixed-mode loading however remains somewhat of a mystery. The failure is believed to be followed by a normal collapse (Van Herwijnen et al. (2010); Gaume et al. (2017)) and a strain softening phase (Fyffe and Zaiser (2007)). The relation between shear failure and normal collapse and the shape of the strain softening function however remain unknown.

As an alternative to experiments on weak snow layers, which are know to be extremely difficult to perform, we present a numerical model, capable of simulating the response of a weak layer sample to mechanical loading. The microstructure of the sample is taken into account by using X-ray microtomography image as the input information. This enables us to study in details the failure and collapse of weak layers.

2. NUMERICAL MODEL AND THE MIXED-MODE LOADING SIMULATIONS

A numerical model on the basis of the discrete element method (DEM) (Cundall and Strack (1979)) has been developed in order to simulate the me-

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chanical response of snow to external loading (Mede et al. (2018)). An X-ray microtomography image of snow is taken as the input information to describe the microstructure of the snow sample. The binary image of the porous structure of sintered grains is segmented into individual grains using an energy-based algorithm (Hagenmuller et al. (2014)) in order to identify individual grains. Following the approach of Hagenmuller et al. (2015), we assume that snow behaves as as a sintered granular material and model individual snow grains as solid unbreakable entities in DEM simulations. Due to complications in contact detection and contact force calculation, grains are usually modelled as spheric in DEM. Since the effect of the microstructure and the shape of ice grains has to be taken into account in the present study, an original method was developed, where the shape of grains is approximated by a set of overlapping spheres clumped into an unbreakable clump (Mede et al. (2018)). These clumps are positioned at respective positions of the grains they represent on the original microstructure image. They are bound to neighbouring grains by cohesive bonds along the faces where the original image was segmented.

A reconstructed cubical sample of snow is exposed to a combination of a constant shearing velocity and constant vertical pressure. Both shear and normal loading are applied to the top face of the sample, while a rigid boundary condition is applied to the bottom face and a continuous boundary condition is applied to all four side-faces The simulation is stopped once the shear strain reaches the value $\varepsilon = 0.05$.

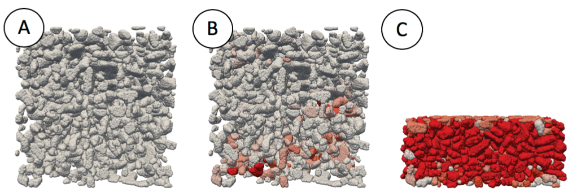

Figure 1: Snapshots of the simulation, showcasing the evolution of damage and strain in the I23 snow specimen.The red colouring of the grains represents the amount of local damage in the form of the percentage of broken cohesive bonds connecting the grain with it's neighbouring grains in the porous matrix. Snapshot A was taken at strain $\varepsilon = 0.000$ and represents an intact specimen; snapshot B was taken at strain $\varepsilon = 0.003$, where a clear localization of damage had already developed; snapshot C was taken at strain $\varepsilon = 0.006$, where the specimen collapse had already taken place.

The described shear simulations under varying values of normal pressure are performed on microstructures, extracted from three different snow samples - sample I23 (rounded grain snow type (RGO), density= 250 kg m^{-3}), sample I15 (rounded grain snow type (RGO), density= 180 kg m^{-3}) and sample 9 (faceted snow (FCDH), density= 180 kg m^{-3}). The choice of samples with the given properties allows us to compare the response of two samples with the same snow type and different densities (samples I23 and I15) on one hand as well as the response of two samples with the same density and different snow type (samples I15 and 9).

The simulations are performed with DEM solver YADE (Šmilauer et al. (2010)). Simulation parameters are chosen as follows: shearing velocity $v = 1$ cm s^{-1}, grain density analogue to that of ice $\rho = 970 \cdot 10^3$ kg m^{-3}, contact friction coefficient analogue to that of ice $\mu = 0.2$, and Cundall's non viscous damping coefficient 0.02. Cohesion is modelled with brittle elastic law, using a contact stiffness $E = 10^8$ Pa and strength $C = 10^6$ Pa. It has been verified that the applied shear rate is low enough to ensure a quasi-static shearing regime. The simulated strain rate is well above the rate of transition from ductile to brittle behaviour, justifying the use of elastic brittle contact law for cohesive bonds between the clumps. It has also been verified that the utilized contact stiffness ensures the simulations are performed in the rigid grain limit (Cundall and Strack (1979); da Cruz et al. (2005)).

3. WEAK LAYER RESPONSE TO SHEAR LOADING UNDER VARYING NORMAL PRESSURES

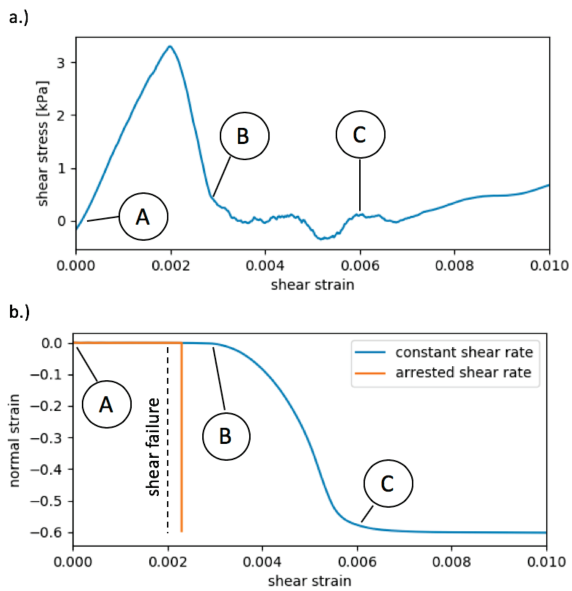

Figure 2: Response of the sample I23 to shearing under normal pressure p=4kPa in terms of shear stress (a) and normal strain (b) with respect to shear strain. The blue curve on both images represents the response of the sample to constant shear rate and the indications A-C refer to snapshots in Fig. 1. The orange curve in image b.) represents the result of the simulation where the shearing was stopped just after the shear failure.

The simulated response of a snow sample to mixed-model loading is first presented graphically in

Fig. 1. Images A-C represent snapshots of the simulated shearing on the sample I23 under the normal pressure p=4kPa. The red colorscale represents the amount of damage inflicted to individual grains in terms of the percentage of broken cohesive bonds with the neighbouring grains. In the image B the damage localization is clearly visible and as the damage propagates through the sample, eventually a normal collapse takes place in the sample (image C), transforming the snow sample into a cohesionless set of grains.

The blue curves on Figs. 2.a and 2.b respectively showcase the shear stress and normal strain response of the sample I23 to shearing under the normal pressure p=4kPa. The indications A-C refer to snapshots in Fig. 1 and should help put these results into perspective. A general response to mixed-mode loading, observed for all three samples can be summarized as following: a quasi-elastic phase, where the shear stress builds up as near-linear function of the shear strain and no noticeable normal strain can be observed. This is followed by a shear failure and if the normal pressure is sufficiently high, a rapid decrease of shear stresses and a normal collapse. After the collapse, the normal strain of the sample remains constant and the sample regains some shear resistance. The shear stresses at this point are a result of friction between the grains of a disintegrated snow.

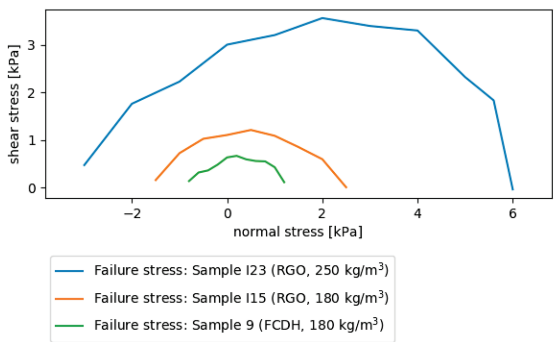

Figure 3: Failure envelopes for the three simulated snow specimens: sample I23 (rounded grain snow type (RGO), density= 250 kg m^{-3}), sample I15 (rounded grain snow type (RGO), density= 180 kg m^{-3}) and sample 9 (faceted snow (FCDH), density= 180 kg m^{-3}).

The shearing simulations were performed on three different reconstructed snow samples under varying values of normal pressure. For each sample the values of failure shear stresses are plotted against the normal pressure of each respective simulation in order to recover the failure envelopes shown in Fig. 3. The failure envelopes qualitatively resemble the experimental findings (Chandel et al. (2014); Reiweger et al. (2015)) and fit the Mohr-Coulomb criterion with a cap. Although the three failure envelopes look qualitatively similar, the quantitative differences are evident. The influence of sample density, which is well established in the scientific community is evident by comparing the failure envelopes of samples I23 and I15, which feature the same snow type and a different density. More interestingly, a somewhat less established effect of the microstructure can be observed by comparing the failure envelopes of samples I15 and 9, which have the same density but consist of different snow types. Lastly, the residual stresses of all three samples seem to follow the same dependency on normal pressure, indicating the same macroscopic friction independently of the studied snow types.

4. SHEAR FAILURE AND COLLAPSE

Finally the relation between the shear failure and normal collapse is addressed. Although a visual inspection of shear stress and normal strain curves on Fig. 2 might suggest a certain delay of the normal collapse with respect to the shear failure point, in the scope of the present study, we prove that the normal collapse is initiated by the shear failure. Additional simulations were run on the same specimen under unchanged loading conditions, where the shear rate was arrested at different points upon shear failure. It was shown that if the shearing is arrested at any point after the shear failure, the normal collapse spontaneously propagates to its final value (orange curve on Fig. 2.b). Additionally, it has been shown that the sample collapse is a dynamic event completely independent of shearing, but rather completely time-driven. Thus, the question of the shape of the strain softening function that was believed to follow the shear failure seems to be completely off the point - the vanishing shear stresses are not a consequence of strain softening, but rather a sign of the dynamic collapse of the sample.

5. CONCLUSION

In the present paper we show that the model previously developed in the scope of this project is capable of simulating large strain response of weak layer samples to mixed-model loading and presents a powerful tool to study the complex mechanics of dry slab snow avalanche release.

The response of three different reconstructed snow samples to mixed-mode shear and normal loading has been simulated. Providing that the normal pressure is high enough, the response of the faceted snow as well as rounded grain snow samples has been shown to consist of a quasi-elastic phase, shear failure, normal collapse accompanied by rapidly vanishing stresses and a residual stress of a decomposed snow. The failure envelopes take the shape of a Mohr-Coulomb criterion with cap, as has already been observed by the experimential investigations. The quantitative differences of the failure envelopes of three different snow samples indicate that not only density but also microstructure of snow have a decisive effect on the failure stresses. The normal collapse of a weak layer was shown to be triggered by shear failure and it has been demonstrated that it spontaneously propagates once the shear failure has taken place. The collapse itself is thus a time-driven process which is completely independent of shearing.

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REFERENCES

Chandel, C., Mahajan, P., Srivastava, P., and Kumar, V. (2014). The behaviour of snow under the effect of combined compressive and shear loading. *Current Science*, pages 888–894.

Cundall, P. and Strack, O. (1979). Discrete numerical model for granular assemblies. *Geotechnique*, 29(1):47–65.

da Cruz, F., Emam, S., Prochnow, M., Roux, J.-N., and Chevoir, F. m. c. (2005). Rheophysics of dense granular materials: Discrete simulation of plane shear flows. *Phys. Rev. E*, 72:021309.

Fyffe, B. and Zaiser, M. (2007). Interplay of basal shear fracture and slab rupture in slab avalanche release. *Cold Regions Science and Technology*, 49(1):26–38.

Gaume, J., van Herwijnen, A., Chambon, G., Wever, N., and Schweizer, J. (2017). Snow fracture in relation to slab avalanche release: critical state for the onset of crack propagation. *The Cryosphere*, 11(1):217–228.

Hagenmuller, P., Chambon, G., Flin, F., Morin, S., and Naaim, M. (2014). Snow as a granular material: Assessment of a new grain segmentation algorithm. *Granul. Matter*, 16(4):421–432.

Hagenmuller, P., Chambon, G., and Naaim, M. (2015). Microstructure-based modeling of snow mechanics: A discrete element approach. *Cryosphere*, 9(5):1969–1982.

Köchle, B. and Schneebeli, M. (2014). Three-dimensional microstructure and numerical calculation of elastic properties of alpine snow with a focus on weak layers. *Journal of Glaciology*, 60(222):705–713.

Mede, T., Chambon, G., Hagenmuller, P., and Nicot, F. (2018). A medial axis based method for irregular grain shape representation in dem simulations. *Granular Matter*, 20(1):16.

Reiweger, I., Gaume, J., and Schweizer, J. (2015). A new mixed-mode failure criterion for weak snowpack layers. *Geophysical Research Letters*, 42(5):1427–1432.

Schweizer, J., Jamieson, J., and Schneebeli, M. (2003). Snow avalanche formation. *Reviews of Geophysics*, 41(4):2–1 – 2–25.

Srivastava, P. K., Chandel, C., Mahajan, P., and Pankaj, P. (2016). Prediction of anisotropic elastic properties of snow from its microstructure. *Cold Regions Science and Technology*, 125:85–100.

Van Herwijnen, A., Schweizer, J., and Heierli, J. (2010). Measurement of the deformation field associated with fracture propagation in weak snowpack layers. *Journal of Geophysical Research: Earth Surface*, 115(F3).

Šmilauer, V., Catalano, E., Chareyre, B., Dorofenko, S., Duriez, J., Gladky, A., Kozicki, J., Modenese, C., Scholtès, L., Sibille, L., Strànskỳ, J., and Thoeni, K. (2010). Yade Reference Documentation. In Šmilauer, V., editor, *Yade Documentation*. The Yade Project, 1st edition. http://yade-dem.org/doc/.