HOW SNOW FAILS

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ABSTRACT: Dry-snow slab avalanches start with a failure in a weak layer below a cohesive slab. Avalanche release models start with an initial crack which may propagate and, depending on the slope angle and the roughness of the fracture surface, lead to a whumpf or an avalanche. In order to investigate how the initial failure forms, we performed loading experiments with a weak surface hoar layer. We found that surface hoar strength decreased with loading rate and slope angle. Possible consequences for slab release are discussed.

1. INTRODUCTION

A prerequisite for dry-snow slab avalanche release is a failure in a weak snow layer below a cohesive slab of ample thickness (e.g. Schweizer et al., 2003). If the failure grows to a sufficiently large crack and the snowpack conditions are favourable for crack propagation, the initial crack can propagate and an avalanche may release.

Most (80%) dry-snow slab avalanches release on either a surface hoar a depth hoar, or a faceted snow layer (Schweizer and Jamieson, 2001) (Figure 1).

As monitoring the initiation process for dry-snow slab avalanches in the field is very challenging (e.g. van Herwijnen and Schweizer, 2008) a more promising approach is to study the failure behavior experimentally in a cold laboratory. In previous laboratory studies on the mechanical behavior mainly displacement controlled shear experiments with homogeneous snow samples were performed. Only in two studies layered samples including a weak layer were tested (Fukuzawa and Narita, 1993; Joshi et al., 2006). Within these studies it was found that the deformation mechanisms of snow depend strongly on deformation speed and snow microstructure, which at the same time changes during deformation.

Displacement-controlled experiments give insight into the material behavior before fracture. However, to study fracture itself, and in particular the processes that lead to fracture, load-controlled (or force-controlled) experiments are needed.

Figure 1: Crown fracture of a skier-triggered avalanche which released on a layer of surface hoar (photo: R. Pajarola).

Camponovo and Schweizer (2001) performed stress-ramp experiments with homogeneous snow with a rheometer, where the snow samples were sheared by rotation. Their experimental results suggest that sintering of snow continuously occurred during the experiments, and only at a high applied stress did the damage process exceed the sintering (or healing) process. The only other modern load-controlled shear experiments, to our knowledge, were recently performed by Podolsky et al. (2008) who pulled a shear frame on a horizontal snow sample with constantly increasing force. They found that snow strength dramatically decreased with increasing loading rate.

We performed loading experiments with a new apparatus especially designed for studying the failure of snow with respect to avalanche release. In this apparatus the snow samples are loaded via the gravitational force. This gives a natural combination of shear and normal load depending on the 'slope angle'.

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2. METHODS

2.1 Harvesting surface hoar samples

Snow samples containing a weak layer are very relevant study objects but also very difficult to transport. Therefore, all our natural snow samples were taken from the study plot next to the SLF cold laboratory. We continuously monitored the snowpack during the winter season by making profiles and observing the snow surface for surface hoar. When we found a suitable weak layer for testing, we took samples from that layer. With suitable weak layer we mean a weak layer which is clearly defined and has sufficiently thick and cohesive layers above and below which allow cutting the samples and transporting them into the laboratory without destroying them. The transporting into the laboratory was done by taking away superfluous snow on top of the sampled area, then cutting the sides of the snow samples with a snow saw, and finally carefully extracting the samples from the snowpack and putting them on a styrofoam plate with a spatula. The samples were then carried into the cold laboratory for storage. In the laboratory the samples were stored under styrofoam hoods for maximum a week at -20°C.

2.2 Shear experiments

The idea behind our force-controlled loading apparatus (Figure 2) was to mimic loading conditions found in a natural snowpack. For a more detailed description of the apparatus we refer to Reiweger et al. (2009) and Reiweger et al. (2010).

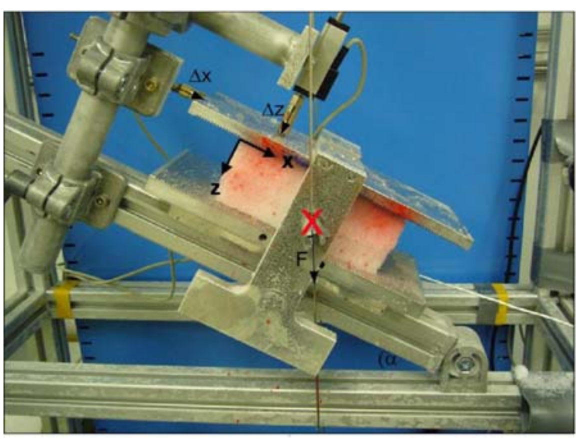

Figure 2: Photograph of a snow sample in the loading apparatus. α denotes the slope angle, F is the force acting on the snow sample, and Δz and Δx denote the compressive and shear displacement of the upper plate.

The relation between shear and normal force was determined by the 'slope angle' α, i.e. by tilting the sample holder. The loading of the upper sample holder was achieved by draining fluid (i.e. alcohol) from a container placed on top of the shear apparatus into a container placed below the snow sample and attached to the upper sample holder. The load, the compressive and the shear displacement were measured with a force and two displacement sensors, respectively.

3. RESULTS AND DISCUSSION

The strength (load at fracture divided by area of the sample) of the surface hoar samples as a function of slope angle and loading rate is shown in Figure 3. We found a significant decrease of strength with increasing loading rate and increasing slope angle.

The decrease of strength with slope angle implies that layers of buried surface hoar are weaker in shear than in compression. This finding suggests that the release of a slab avalanche is the result of a failure within the weak layer due to shear deformation rather than due to compressive deformation. If so, this would also mean that the collapse of the weak layer which is typically observed when weak layers fracture (e.g. van Herwijnen et al., 2010) is rather a consequence of the initial failure.

The strength of the surface hoar samples decreased with loading rate. This is obviously in accordance with previous findings (e.g. de Montomollin, 1982; Schweizer, 1998). The rate dependence is exemplified by the observation that a skier or explosives may trigger an avalanche due to fast loading, even if the weight of a skier is lower than the weight of snow above the weak layer.

At low loading rates and at low slope angle the samples did not fracture at all, but showed considerable deformation. At the end of the loading process, the weak layers' microstructure was completely different, but the samples were still intact, i.e. the weak layer was able to carry the load. This observation suggests that the small fractures which must have happened within the weak layer must have healed again during the loading process.

For avalanche release this implies that an initial failure within a surface hoar layer which is too small to propagate (a so-called sub-critical fracture) may heal again if the loading rate is small enough. Healing of fractured weak layers has been observed in the field (Birkeland et al., 2006). However, in these two cases the fracture propagated, but the slabs did not slide as the slopes were not steep enough.

Due to the brittleness of the surface hoar layer we could only perform a limited number of experiments since many samples failed during mounting within the apparatus. However, these were the first loading experiments with surface hoar carried out under controlled laboratory conditions. Moreover, the samples' fragility underlines the layers' relevance for dry-snow slab avalanche release.

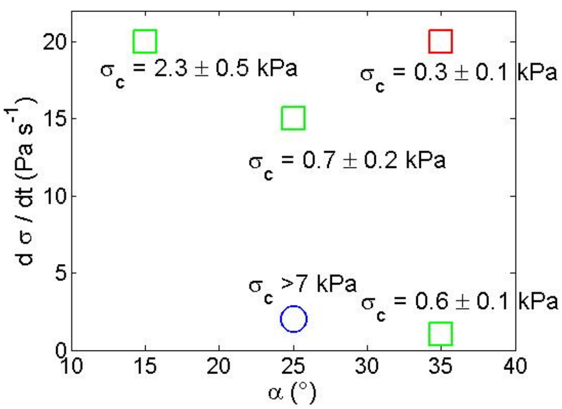

Figure 3: Fracture stress σ_c dependent on loading rate and slope angle for surface hoar samples. Squares denote fracture, while the circle denotes no apparent fracture. The colors illustrate the magnitude of the fracture stress (*N* = 10).

4. CONCLUSIONS AND OUTLOOK

For the first time loading experiments with samples containing a weak layer of buried surface were performed. Our results show that surface hoar is weaker in shear than in compression and that its strength decreases with increasing loading rate.

The absence of catastrophic failure at low loading rates and slope angles suggests that small fractures within a surface hoar layer have the ability to heal, so potential 'hot spots' seem a rather transient phenomenon.

For the future it would be relevant to perform similar experiments also with other weak layers such as depth hoar in order to generalize the results and their implications for avalanche release.

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