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# Failure of a layer of buried surface hoar

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[1] In order to study the formation of the initial failure leading to dry-snow slab avalanche release, we performed loading experiments in a cold laboratory with natural samples including a layer of buried surface hoar. The experimental setup was such that the layered snow samples were loaded continuously for various tilt (slope) angles; loading rates varied between 1 and 20 Pa $s^{-1}$. The stress at fracture decreased with increasing loading rate and increasing slope angle, i.e., increasing shear component of the load. The latter result means that the layer was stronger in compression than in shear which is attributed to the particularly anisotropic nature of layers of buried surface hoar. Particle image velocimetry revealed that almost 90% of the sample's global deformation was concentrated in the weak layer. For avalanche release our results imply that the shear component of deformation is of particular importance for failure initiation. **Citation:** Reiweger, I., and J. Schweizer (2010), Failure of a layer of buried surface hoar, *Geophys. Res. Lett.*, *37*, L24501, doi:10.1029/2010GL045433.

## 1. Introduction

[2] Weak snowpack layers are a prerequisite for dry-snow slab avalanches to occur. The slab will only detach and develop its destructive power after a sufficiently large area of the weak layer has failed so that the fracture in the weak layer below the slab will spontaneously propagate upward, downward, and across the slope followed by tensile fracture at the crown of the slab [e.g., *McClung*, 1981; *Schweizer et al.*, 2003]. Due to the highly porous nature of snow the fracture in the weak layer means structural failure manifesting itself by collapse [*Jamieson and Schweizer*, 2000]. This vertical displacement, varying from less than a millimeter to more than a centimeter has consistently been observed for various types of weak layers [*van Herwijnen and Jamieson*, 2005]. Whereas with field tests such as the propagation saw test [e.g., *Gauthier and Jamieson*, 2008] conditions for fracture propagation can be studied, it presently remains unclear how the initial failure originates. The question has been raised whether the initial failure is in compression or shear [*Birkeland et al.*, 2009], i.e., whether the shear failure leads to the collapse of the weak layer or whether the collapse of the weak layer is the origin of the shear failure.

[3] Many fatal avalanches release on buried surface hoar [e.g., *Jamieson and Johnston*, 1992]. The truss-like structure – large, thin crystals standing upright with hardly any lateral bonds and large pore space between them [*Jamieson and Schweizer*, 2000] – makes layers of buried surface hoar prone to fracture and many remotely triggered avalanches involve surface hoar. Surface hoar formation is typically widespread, but size varies over terrain [*Feick et al.*, 2007]. Once buried, layers of surface hoar may be responsible for snow instability for several weeks [e.g., *Hägeli and McClung*, 2003; *Schweizer and Kronholm*, 2007]. The relatively simple microstructure also enables model development [e.g., *Reiweger et al.*, 2009].

[4] From displacement-controlled laboratory experiments with rounded grained snow, it is known that snow under shear loading is a pressure sensitive and strain-softening material [*McClung*, 1977]. Snow strength depends on loading rate [*Narita*, 1983; *Schweizer*, 1998]. *de Montmollin* [1982] suggested that the rate dependence of snow strength – and ultimately the strain softening behavior – might be the consequence of sintering. Previous experimental results on strength have not been achieved under load-controlled conditions and very rarely have weak layers been tested under controlled laboratory conditions [*Fukuzawa and Narita*, 1993].

[5] The aim of our experiments is to study the failure behavior of a natural layer of buried surface hoar. We focus on the conditions favoring the formation of the initial crack – the crack which might lead to fracture propagation and the subsequent release of an avalanche if the slope is steep enough. We do not study fracture propagation itself, as our samples are too small to do so. Fracture propagation is best studied with field tests [e.g., *van Herwijnen et al.*, 2010].

## 2. Methods

[6] We have collected samples including a thin layer of buried surface hoar crystals from the study plot located beside the SLF cold laboratory at Davos, Switzerland. The surface hoar crystals were striated wedge-shaped plates (sector plates). The layer was about 5 mm in thickness and the layers above and below consisted of small rounded grains (RG) according to the ICSSG [*Fierz et al.*, 2009].

[7] A total of 19 samples were cut and stored for up to two days at −20°C prior to testing. An overview of the samples' properties is given in Table 1. The thickness of the weak layer was always the same (~ 5 mm), while the thickness of the upper and lower layers slightly varied due to sample preparation. Sample size was 125 mm × 100 mm × 65 mm (length × width × height). Due to the fragile nature of the weak layer 9 out of 19 samples broke during preparation or mounting, resulting in a relatively small dataset. However, this demonstrates the weakness of this layer and indicates that results obtained with it should be relevant for dry-snow slab avalanche release.

[8] Samples were tested at −6°C using the load-controlled shear apparatus (Figure 1) described by *Reiweger et al.* [2010] including particle image velocimetry (PIV). Within the apparatus, the snow samples were tilted by a 'slope angle'

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**Table 1.** Density, Height and Snow Type of the Natural Snow Samples Tested[a]

| Layer | Density (kg m$^{-3}$) | Height (mm) | Snow Type |
|---|---|---|---|
| upper | 160 | 30 | RG, 0.5 mm, 1 |
| weak layer | n/a | 5 | SH, 5 mm, 1 |
| lower | 160 | 30 | RG, 0.5 mm, 1–2 |

[a] Snow type is described as grain type according to *Fierz et al.* [2009], average grain size and hand hardness index (1, Fist; 2, Four fingers).

and loaded via the gravitational force. This setup provides a combination of shear and normal load similar to conditions in a natural snowpack. Loading rates varied between about 1 Pa s$^{-1}$ and 20 Pa s$^{-1}$. The lower rate is relatively slow, but still about 5–10 times faster than a typical intense snowfall. The 'slope angles' tested were 15°, 25° and 35°.

## 3. Results

[9] Due to the limited number of natural samples we could only perform 2 tests for one set of parameters (loading rate and 'slope angle'). The results of the successful experiments are compiled in Table 2. At the fast loading rate (>3 Pa s$^{-1}$), most samples fractured within several tens of seconds. Two of the four samples tested at the slow loading rate (≤3 Pa s$^{-1}$) did not fail before the maximum possible load was reached, namely those for $\alpha = 25°$. Only the samples loaded at the steeper 'slope angle' fractured. In general, the fracture stress decreased with increasing 'slope angle' (Figure 2).

[10] The fracture always took place between the layer of buried surface hoar crystals and the adjacent layer, i.e., at either the upper or lower boundary of the surface hoar layer. After fracture we observed many fallen down but intact surface hoar crystals, indicating that they had only toppled during fracture of the layer, i.e., the surface hoar crystals did not break apart.

[11] For a given 'slope angle' the fracture stress decreased with increasing loading rate. Shear strain at fracture ranged from 0.4 to 7% depending on loading rate and 'slope angle'. The global (sample average) shear strain rates were between $8 \times 10^{-5}$ and $7 \times 10^{-4}$ s$^{-1}$. These strain rates are smaller than the critical strain rate for the ductile-to-brittle transition commonly reported for homogenous snow samples [e.g., *Schweizer*, 1998]. Even at the slow loading rates the strain increased almost linearly with time, i.e., we hardly observed strain softening before catastrophic failure.

[12] For all experiments the shear strain was substantially larger than the compressive strain, although the compressive stress was always larger than the shear stress (as the slope angle was always <45°). No dilatancy was observed, i.e., the slope-normal deformation was always compressive.

[13] The PIV analyses revealed that most of the shear strain was concentrated in the weak layer. Figure 3 shows the strain within the weak layer $\varepsilon_{\mathrm{wl}}$ (measured indirectly by PIV) divided by the total strain $\varepsilon_{\mathrm{tot}}$ (both measured shortly before fracture) as a function of the inverse relative thickness of the weak layer $h_{\mathrm{tot}}/h_{\mathrm{wl}}$. Figure 3 also includes data from displacement-controlled shear experiments; these three samples consisted of the same snow types and had the same properties as samples A1–A10 (Table 1). If all the deformation would be concentrated within the weak layer, the points in Figure 3 would lie on a straight line with slope 1. The slope of the fitted line was 0.87 ± 0.02, which means that on average almost 90% of the shear strain was concentrated within the weak layer. No similar concentration of compressive strain within the weak layer was observed.

## 4. Discussion

[14] Due to the fragile nature of the weak layer tested, we only obtained a limited number of results. The relatively small sample size gives a rather unfavorable area to height ratio for the whole sample. Studying the deformation during the experiment, though, we saw a concentration of deformation within the weak surface hoar layer. This is also the location where the samples fractured. Considering the thickness of the weak layer compared to its planar extension, the area to height ratio becomes acceptable.

[15] Also related to the small sample size is the observation that catastrophic failure occurs relatively soon. *Sigrist et al.* [2005] estimated the fracture process zone for fine grained snow to be in the order of at least one centimeter. For our grain size it can be expected to be even larger, i.e., a significant fraction of the sample size, implying that the strength values measured within our experiments are biased by a size effect. Accordingly, in a natural snowpack catastrophic failure would only occur if a crack the size of our sample propagated. If no propagation occurred, the crack would eventually heal again. Our samples were too small to study fracture propagation. The focus with our results is not on the actual strength values but on the trend of decreasing strength with increasing loading rate and 'slope angle'. The loading rate dependence, the strength anisotropy (dependence on 'slope angle'), and also the strain concentration within the weak layer are expected to be independent of sample size. Our laboratory experiments are related to failure initiation as we study the development of the initial crack needed for fracture propagation. To study fracture propagation field tests with large

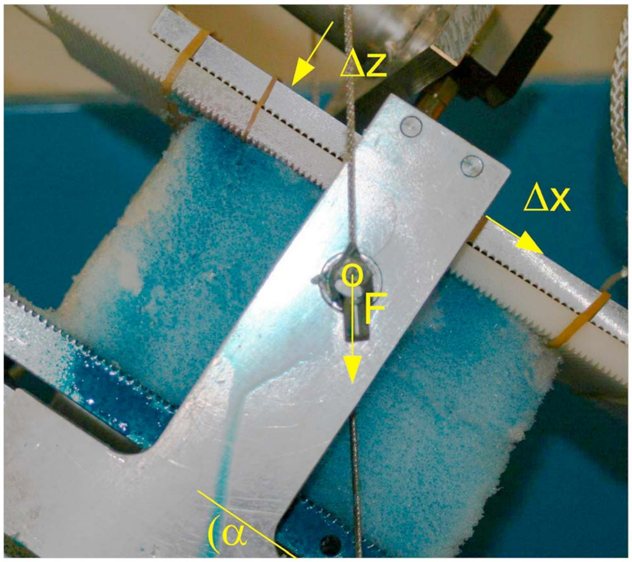

**Figure 1.** Photograph of a snow sample in our loading apparatus. $\alpha$ denotes the slope angle, $F$ is the force acting on the snow sample, and Δz and Δx denote the compressive and shear displacement of the upper plate.

**Table 2.** Test Results for Strength (Stress at Fracture) as a Function of 'Slope Angle' and Loading Rate[a]

| Sample | Slope Angle $\alpha$ (°) | Loading Rate (Pa $s^{-1}$) | Time to Fracture (s) | Shear Strain at Fracture | Strength $\sigma_f$ (kPa) | Shear Strain Rate ($s^{-1}$) |
|---|---|---|---|---|---|---|
| A1 | 25 | 19 | 95 | $7.3 \times 10^{-3}$ | 0.84 | $7.7 \times 10^{-5}$ |
| A2 | 25 | 12 | 40 | $8.2 \times 10^{-3}$ | 0.50 | $2.1 \times 10^{-4}$ |
| A3 | 25 | 1 | - | - | >7 | $1.0 \times 10^{-5}$ |
| A4 | 35 | 20 | 15 | $5.0 \times 10^{-3}$ | 0.36 | $3.3 \times 10^{-4}$ |
| A5 | 35 | 3 | 220 | $1.7 \times 10^{-2}$ | 0.61 | $7.7 \times 10^{-5}$ |
| A6 | 35 | 21 | 13 | $4.1 \times 10^{-3}$ | 0.26 | $3.2 \times 10^{-4}$ |
| A7 | 35 | 3.3 | 120 | $5.0 \times 10^{-2}$ | 0.50 | $4.2 \times 10^{-4}$ |
| A8 | 25 | 3 | - | - | >7 | $1.0 \times 10^{-5}$ |
| A9 | 15 | 21 | 90 | $6.1 \times 10^{-2}$ | 1.9 | $6.8 \times 10^{-4}$ |
| A10 | 15 | 20 | 110 | $7.0 \times 10^{-2}$ | 2.6 | $6.4 \times 10^{-4}$ |

[a] Also given are the loading time until fracture, the global shear strain at fracture, and the average global shear strain rate.

samples are needed, such as the propagation saw test developed by *Gauthier and Jamieson* [2008] and *Sigrist and Schweizer* [2007].

[16] The decrease of strength with loading rate is in agreement with previous measurements with displacement-controlled experiments [e.g., *Schweizer*, 1998] and statistical evidence on the effect of precipitation intensity on avalanche hazard probability [*Perla*, 1970]. It is also in accordance with the observation that a skier (or explosives) may trigger an avalanche due to fast loading, even if the load applied by the skier is lower than the (slowly accumulated) load of the snow above the weak layer.

[17] The slope of the straight line in Figure 3 gives the displacement within the weak layer $\Delta_{WL}$ divided by the total displacement $\Delta_{tot}$ measured at the upper plate. The displacement of the lower layer was zero since the lower plate was fixed. A high ratio of $\Delta_{WL}/\ \Delta_{tot}$ then implies a strong concentration of strain within the weak layer and merely translation of the upper layer. Consequently also the strain rates in the weak layer were about one order of magnitude larger than the global strain rates. The strain (and thereby also strain rate) concentration leads to good agreement with the critical strain rate of about $1 \times 10^{-3}$ $s^{-1}$ for the ductile-to-brittle transition reported for homogeneous snow samples [*Schweizer*, 1998]. The lower critical strain rate ($1 \times 10^{-4}$ $s^{-1}$) reported by *Narita* [1983] is probably related to the fact that he performed tension experiments, whereas within our experiments the snow was loaded in a combination of shear and compression. Note that our samples represented the limiting case of all three layers having roughly the same hardness, i.e., the upper and lower layers were also rather soft. In a configuration with the upper and/or lower layer being substantially harder than the weak layer (as is typical for an avalanche snowpack) [e.g., *Schweizer and Jamieson*, 2003] the strain concentration we found would probably even be enhanced. Concentration of deformation within a relatively thin layer is a typical pre-failure behavior, often called shear bands, in failure leading to landslides [e.g., *Palmer and Rice*, 1973].

[18] We could not find a concentration of compressive deformation in the surface hoar layers studied before catastrophic failure – at failure the whole sample was destroyed and thereby compressed. The lack of compressive deformation may be due to the fact that we are dealing with a mono-crystalline layer which cannot easily be compressed by rearranging grains unless the whole layer collapses. On the other hand, our compressive strains were often very small, maybe too small for finding any significant trends with PIV analysis.

[19] We did not measure strain softening for the surface hoar samples we tested, although we did measure strain softening within our experimental setup with homogeneous

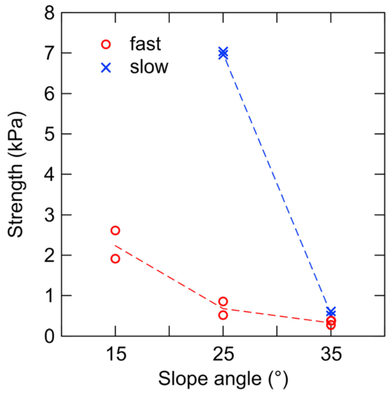

**Figure 2.** Strength as function of slope angle and loading rate. The loading rates were grouped into low (≤3 Pa $s^{-1}$) and high ($N = 10$).

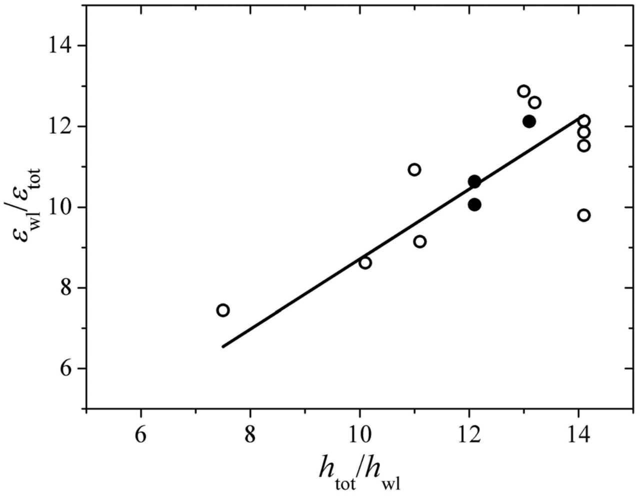

**Figure 3.** Relative shear strain within the weak layer as a function of the inverse relative thickness of the weak layer ($N = 13$). The open circles mark the results of the loading experiments while the full circles mark the results of the displacement-controlled shear experiments.

samples [*Reiweger et al.*, 2010]. We assume that the strain softening for surface hoar is very small due to the particular microstructure of layers of buried surface hoar. Surface hoar crystals may tilt, topple, or even break, but there seems to be hardly any possibility for grain rearrangement without catastrophic failure.

[20] The dependence of strength on slope angle shows that layers of buried surface hoar are weaker in shear than in compression – this already became obvious (purely qualitatively) during sample preparation when typically disturbances in shear caused many samples to fail. The weakness in shear has often been proposed [e.g., *McClung and Schaerer*, 2006, p. 77], but to our knowledge so far has never been shown. For depth hoar layers the anisotropic failure behavior has already been postulated by *Akitaya* [1974]. The dependence of strength on loading direction is probably related to the strong anisotropy of the microstructure in layers of buried surface hoar. *Jamieson and Schweizer* [2000] observed that surface hoar layers were relatively stiff in compression, but susceptible to shear. This result is of particular relevance for the initiation of naturally (spontaneously) releasing dry-snow slab avalanches. The weak layers are loaded by the weight of the overlaying layers, so under mixed compressive and shear load – with the compressive load always dominating below 45°. Nevertheless, our results suggests that initiation of spontaneous avalanches is rather due to failure caused by shear than by compressive deformation. Our results should not be interpreted in the way that as the slope angle increases from 15 to 35°, the strength decreases by a factor of 3–5, but simply that with increasing slope angle, the shear component increases obviously promoting failure. This is in agreement with the observation that the frequency of natural avalanching increases with increasing slope angle, at least in the range of about 30–45°.

[21] Our results may not be applicable for skier triggered avalanches since time to failure was at least 13 s in our experiments, i.e., the loading rate was too slow compared to the loading by a skier.

## 5. Conclusions

[22] We have performed a series of strength tests with a bidirectional load-controlled test apparatus with layered samples containing a natural layer of buried surface hoar. These kinds of layers are known to be weak and frequently form the failure layers of dry-snow slab avalanches. For the first time, the failure behavior of a natural, particularly fragile weak layer was characterized.

[23] Our results confirm that strength decreases with loading rate, at least within a range from 1–20 Pa $s^{-1}$. The shear strain was concentrated in the weak layer and was in most cases about 10 times larger than the global strain. The strain concentration factor depends on the thickness of the weak layer in relation to the sample thickness. In a natural snowpack the concentration factor might well reach a value of 100. Considering the concentration of shear strain within the weak layer, the strain rate within the weak layer was about $1 \times 10^{-3}$ $s^{-1}$. As we observed brittle failure behavior in 8 out of 10 tests, this strain rate value agrees with the critical strain rate typically reported for the ductile-to-brittle transition for homogenous snow samples.

[24] By varying the 'slope angle' the amount of mixed mode loading (compression vs. shear) varied. The fracture stress decreased with increasing slope angle. This demonstrates that layers of buried surface hoar are weaker in shear than in compression. Probably the largely anisotropic, truss-like structure of these mono-crystalline layers is responsible for the dependence of strength on loading direction. The anisotropic failure behavior suggests that the initial failure leading to natural dry-snow slab avalanche release is rather caused by the shear component of deformation than by the compressive component – at least if the failure layer consists of surface hoar.

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