Improvements by Measuring Shear Strength of Weak Layers

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Key words: Snow slab, weak layers, strain rate, shear strength, measuring procedures

ABSTRACT

Concurrent measurements in situ of the shear strength and strain rate of weak layers or interfaces have not been executed up to now. In order to uncover the relationship between the two parameters and to clarify if the usual loading times (0.1 to 3 seconds) were adequate to produce brittle fractures parallel acceleration and deformation measurements were performed. Both additional measurements show that the critical strain rate limit for brittle fractures is always exceeded, thus the dynamic loading of a moving skier is well reproduced by such shear frame measurements. The measuring procedures, the environmental conditions and the measured shear strength values are presented as well as some error sources. Finally the practical consequences of such measurements are displayed by some thereof calculated relationships between strength, stress and stability.

INTRODUCTION

Slab avalanches are most often released in weak layers or interfaces. In order to explain a posteriori such releases or to forecast a slab situation, it is common practice to approximate a mechanical stability index using values of shear strength and overburden stresses of the slab layers measured in the field (and e.g. of an additional skier). However because the strain rate of these strength values is not measured concurrently, there is some doubt, if the dynamic of these measurements is representative for the brittle behaviour which generally is attributed to skier-triggering of slabs. In order to clarify the type of fracture mode for our field measurements, we decided to combine the strength measurements with acceleration and deformation measurements.

EXPERIMENTAL APPARATUS

The instrumental set-up used in our field campaigns is shown in Fig. 1.

The used shear frame is the so called "Swiss" shear frame. This stainless steel frame has six cross-members, is sharpened at the lower edges and has an area of 0.05 m2 (0.2 x 0.25 m). The total weight with mounted accelerometer is 0.85 kg.

The applied shear force was measured with an electronic force gauge attached to the frame with two steel hooks. The gauge range is ± 490 N with a precision of ± 1 N. The stress is obtained, dividing the force by the frame area.

In order to obtain the strain rate and the strain during the experiment, we have mounted an accelerometer onto the shear frame. Integrating the measured acceleration we are in a state to calculate the displacement velocity of the frame and the strain rate, scaling the velocity with the frame length. Integrating the velocity we can calculate the displacement of the frame and the strain (Fig. 2). For one third of the measurements we have mounted on the shear frame also a sensor, which measures directly the displacement. We did not use it for every experiment, because a lot of time was required to fix the sensor in the snow cover or underground carefully. The analog outputs of the three sensors were wired with cables to a signal conditioner and finally to a laptop computer, where we recorded the measured data. The comparison between the measured and the calculated (from acceleration) displacement show a fair agreement (Fig. 3).

The shear force, the frame acceleration and, when used, the displacement length were continuously recorded with a scan frequency of 5 kHz (the time resolution is hence 0.2 ms) for about 3 s.

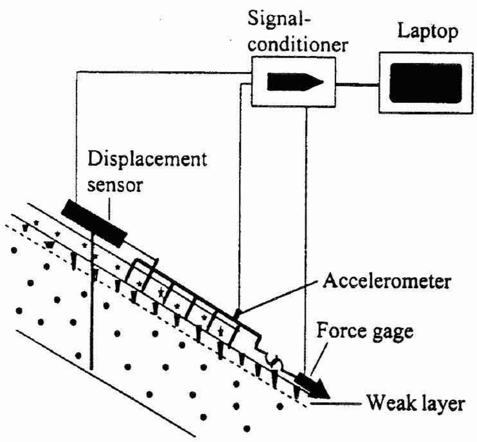

Fig. 1. The instrumental set-up used in our field campaigns.

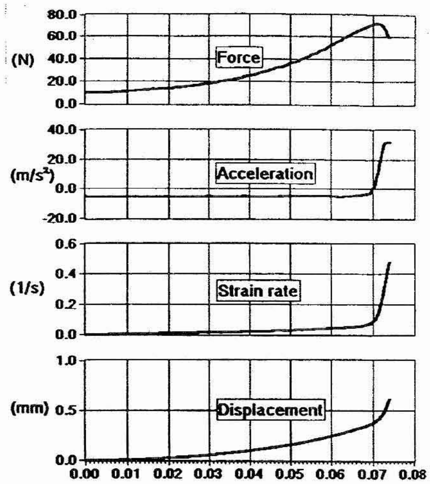

Fig. 2. An example of measured force, acceleration and of calculated strain rate and displacement .

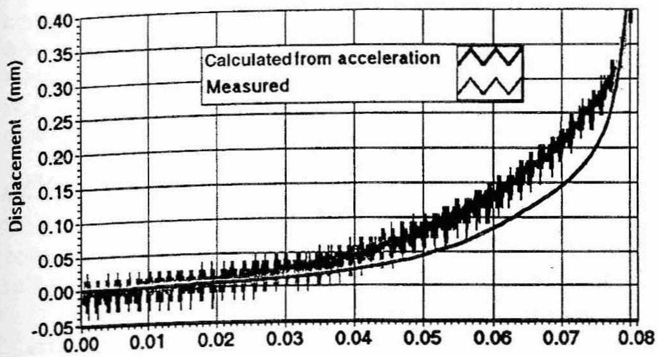

Fig. 3. Measured and from parallel acceleration measurement calculated "displacement-time" curves.

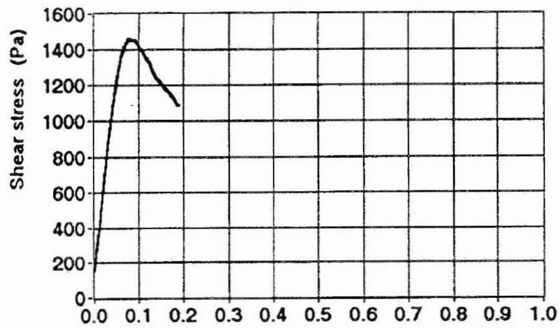

Fig. 4. Typical stress-strain curve, which implies a quasi-linear relationship up to the brittle fracture point. The measured peak value corresponds to the shear strength of the weak layer.

MEASUREMENTS AND RESULTS

During 15 field campaigns in the winter 1995/96 roughly 200 singular shear measurements have been carried out. Due to occasional instrumental deficiencies, sample rupturing before measuring or irregular shear surfaces only about 60% of these measurements could be analyzed in detail.

The main deformations and the failures took place exclusively in these selected thin weak layers or interfaces, which contained mainly low viscosity grain forms: surfaces hoar, faceted crystals, depth hoar or a mixture of them (Föhn, 1993). In some cases also a small percentage of rounded and some melt-freeze grains were admixed.

A typical shear stress-strain curve of these measurements is shown in Figure 4.

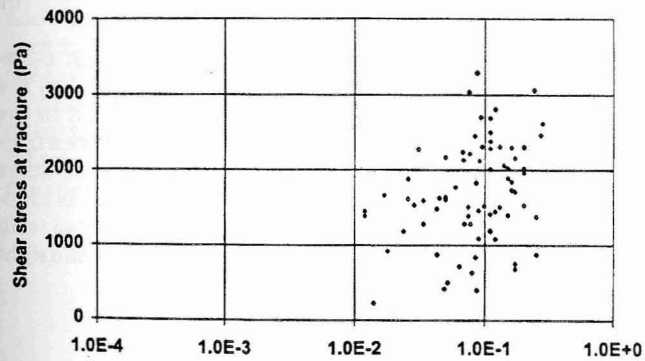

Fig. 5. Strain rate dependency of the measured fracture stresses. The scattering of the points is mainly due to the fact that various weak layers at different dates have been measured. However, the points are all situated well beyond the critical strain rate of 10^{-4} s^{-1} which is accepted as lower limit for brittle fractures.

Almost all weak layers showed this brittle manner, i.e. this same type of rupture curve with a linear rise, a marked peak (maximum fracture force) and a fast drop. The peak values, i.e. the so called cohesion values were then used to calculate the shear strength for our unit samples (0.2 x 0.25 m). It is obvious from all the measured curves that such weak layers show a linear behaviour between stress and strain, thus the Hook law may be applied: $\beta = E\ \varepsilon$, where β describes the shear strength at fracture time, $\varepsilon = dl/l$ the strain of the sample of length l. E stays for the Young's Modulus, the coefficient of elasticity. The mean temperature of the weak layers or interfaces was 5.5°C ± 2.7°C. The total temperature range was -2.6°C to -12.0°C. Johnson (1995) yields a possible explanation for a more or less elastic behaviour: "..snow may exhibit an initial quasi-elastic deformation until the bonds between snow grains fail...".

Analyzing additionally the relationship between the stress and the strain rate ε = d/dt, we observe on Fig. 5, that all measured points are situated well beyond the value ε= 10-4s-1, which is commonly accepted as the needed strain rate for brittle fractures (Narita, 1983, Fukuzawa and Narita, 1993; McClung and Schaerer, 1993).

The shear strength range and the strain rate range of our thin weak layers or interfaces were, 250 to 4000 Pa and

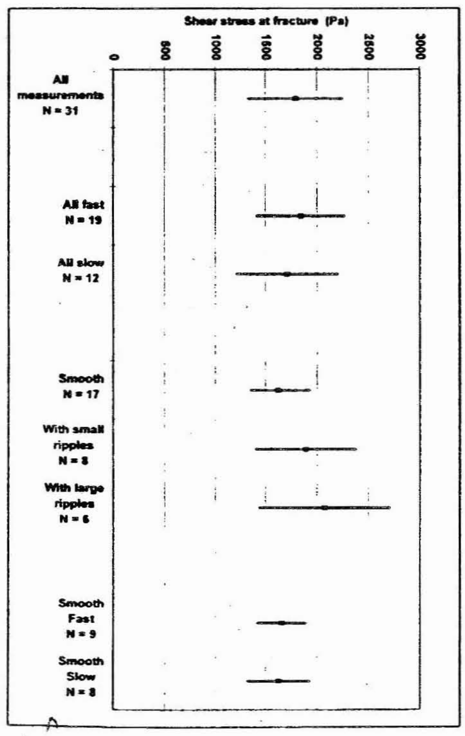

Fig. 6. Dependency of the measured fracture stress on the speed of the pulling action (fast or slow) and on the quality of the rupture surface (smooth, small or large ripples).

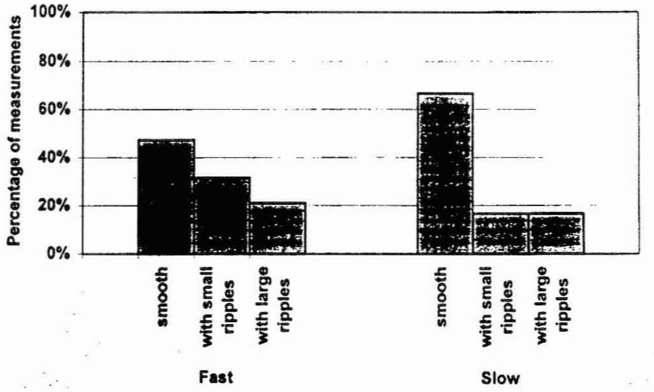

Fig. 7. Relative frequency of shear frame measurements, which showed smooth or rough fracture surfaces, depending on the pulling speed.

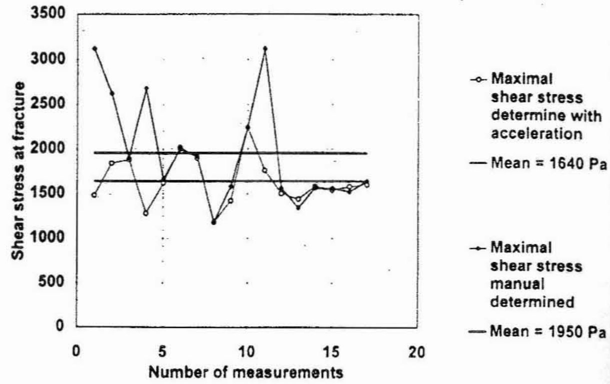

Fig. 8. Differences of measured fracture stress due to the measuring method (measuring with or without acceleration).

10^{-2} to 10^{-1} s^{-1} respectively.

Shearing and fracturing the weak layers by a fast or slow pull action (within 0.1 s and 2.5 s respectively) produces definitely a brittle fracture at high strain rate, followed by a catastrophic failure for the given weak layer area, similarly as during the initiation of larger snow slabs in dry snow conditions. In the fast pull case the critical displacement rate amounts - according to the above data - to 2.5 mm/s, in the slow pull case to roughly 0.4 mm/s.

As we see from the Fig. 6, the measured stress at fracture or strength of each sample depends slightly on the way we measure (fast or slow) and if the rupture surface was smooth or rough (covered with small or large ripples). Such ripples indicate an imperfect shear fracture, resulting in higher force and strength values.

In general "slow pull" measurements yield better results, because the control of the pulling action, e.g. the direction along the slope line, is better guaranteed during a slow pull. Therefore as we see from Fig. 7, slow pulls result more often in smooth shear surfaces, which improve the results.

It is important to note that a fast pull as well as a slow pull are sufficient to reach the high strain rate range, which guarantees a brittle fracture. Therefore such shear frame measurements are representative, prognostic tools for slab formation processes and various artificial avalanche release mechanisms. According to results of Schweizer et al. (1995) a skier exerts by skiing (weighting or jumping) peak shear stresses in the same order of magnitude as our strength values and also in brittle manner thus the most important prerequisites for a skier triggered slab are approachable.

We have to mention that a up to now hidden error source for shear frame measurements has been localised so far as under certain conditions several force-peaks are visible on a force-time diagram after the fracture. Common shear strength measurements reveal only the maximum peak, which sometimes may not represent the fracture peak. In such cases only a parallel measured displacement curve may indicate the right peak, i.e. when the fracture really happened. This error source contributes generally between 10 to 20 %, but especially when very weak layers are measured (shear strength <500 Pa), this fact may double the peak-strength value (Fig. 8).

The shear strength has two basic components: cohesion and friction. The cohesion is mainly related to the bond strength of the snow grains and the friction to the weight of the snow layer above. As long as we have a constant velocity of displacement the friction force stays smaller than the cohesion force, thus the first peak is identical with the maximum peak, i.e. we measure also with common shear frame measurements the cohesion, the right

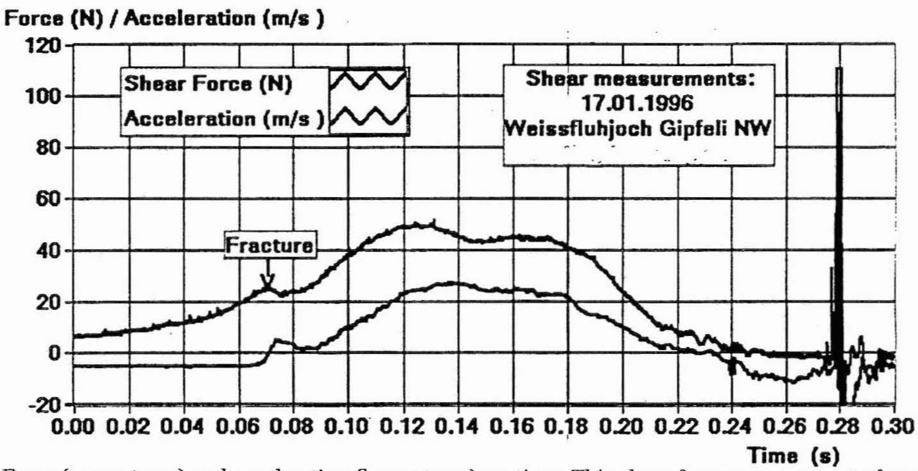

Fig. 9. Force (upper trace) and acceleration (lower trace) vs. time. This shear fame measurement of a very weak layer shows three shear force peaks. Only the first one is relevant, where the fracture happened.

component. As soon as the velocity is changing, we measure additional friction forces (and peaks) which may be larger than the cohesion forces, thus the maximum peak is governed by friction. This situation and the consequences are represented on Fig. 9.

PRACTICAL CONSEQUENCES

Due to the experiences during the last winter we plan to construct a new compact shear frame measuring set, which integrates acceleration measurements and a handy data acquisition system. It is also planned to replace the heavy and rigid hook- system of the "Swiss" frame by a flexible cord in order to reduce slope-angle related errors during the pulling action.

At last we would like to stress the practical importance of such shear frame measurements by showing some useful relationship between measured parameters and thereof calculated stability terms.

Figure 10 shows a linear fit of the shear strength-cohesion relationship which was calculated by all data collected in the last winters during the field campaigns. The measured cohesion data have been corrected for size effects, i.e. adjusted to strength of large areas i.e. the Daniels strength (Föhn, 1987).

Fig. 11 displays the calculated shear stresses on the various observed weak layers or interfaces as a function of the depth of the slab layers. Scatter is due to variation in slab layer (density, slope angle). The shear stress due to the slab layers, named "snow" increases linearly with the slab depth, whereas the skier stresses imply an exponential behaviour. This means that a line load (skier) loads the weak layers close to the surface much more than the ones buried deeper in the snowpack as modeled and measured by Schweizer (1993, 1995). From Fig. 11 we may also see that weak layers deeper than 1 m below the surface will

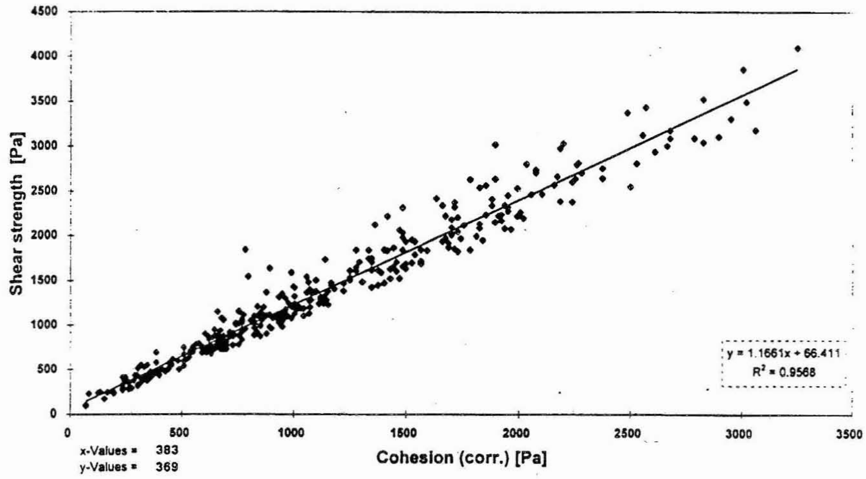

Fig. 10. Relationship between measured and for size effects corrected cohesion and shear strength.

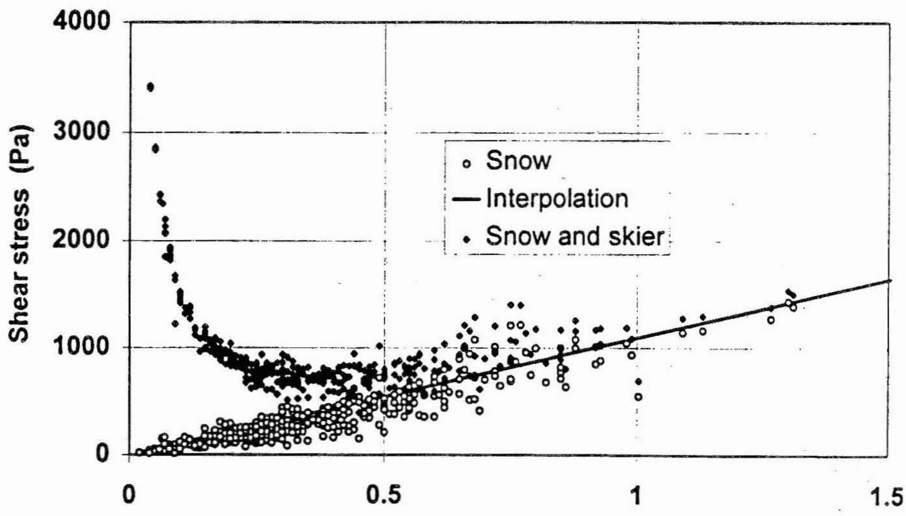

Fig. 11. Calculated shear stress vs. slab layer depth for various snow cover conditions. The partial shear stress of the slab layers (snow) and of a skier standing atop of this layers is given.

only be slightly influenced by a skier under normal conditions. This result yields also the hint to practitioners that trenches for Rutschblocks or profiles may often be limited to this depth.

Finally Fig. 12 shows the approximate relationship between the skier stability index S' (or SS, Jamieson, 1995) and the measured shear strength by various snow conditions. The shear strength is obviously a very important parameter for the stability. Shear strength values smaller then 500 Pa are definitely insufficient (S' ≤ 1.0) whatever the exact shear stress will be, values smaller then 1 kea probably also, because of the safety margin of S' ≥ 1.5, which has to be taken into account when analyzing safety aspects (Föhn, 1987, Jamieson and Johnston, 1993).

CONCLUSIONS

By use of an adequate instrumentation (digital force gauge, accelerometer, displacement-meter) it is possible to determine by shear frame measurements not only the shear strength, but also the shear strain and strain rate independently. Thus after all also the strain rate dependence of shearing thin weak layers could be determined in situ on representative small slopes. This is important because snow samples containing weak layers may rarely be transported into cold labs for measurements without rupturing.

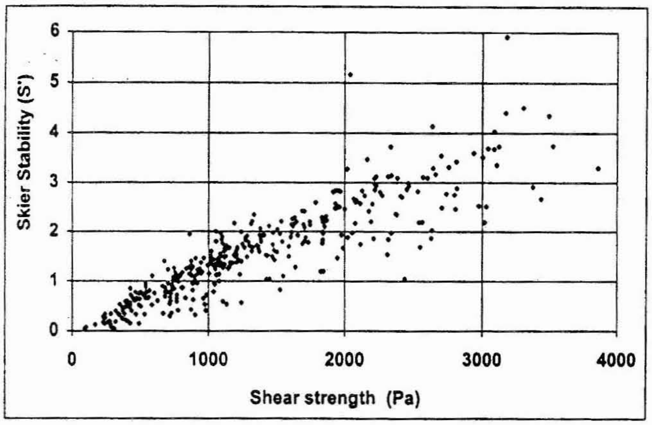

Fig. 12. Snowpack stability index (S') of a snowpack loaded by a skier vs. shear strength measured over many winters by various conditions. Weak layer shear strength smaller than 1000 Pa indicate more or less instable conditions if a safety margin of S' = 0.5 is included (S' ≤ 1.5 means triggering of slabs probable).

The results clarify the following points:

- The "fast" pull range (0.1 ≤ dt ≤ 3 s) yields a brittle fracturing with a strain rate of 10^{-2} to 10^{-1} per second, which is well beyond the critical limit for brittle fractures 10^{-4} per second.
- Dry weak layers show by shearing a more or less linear elastic behaviour in the limited strain range experienced.
- It seems that by such measurements also the fast fracturing process of a skier is well approximated.
- Depending on the individual pulling action, the shear strength values, measured up to now without recording the force-time relationship, could have been partially overestimated, mainly in the case of very weak layers.

ACKNOWLEDGEMENTS

For their expertise and field work at various times, we are grateful to Charles Fierz, Georges Krüsi, Christof Oberschmied. Thanks to André Roth for the photos.

Many thanks also to many unnamed part-time students, who helped in the field and to Stefan Felix, Marco Gaia, Urs Liebing, Christoph Marty and Kaspar Plattner, who helped compile the data of the previous field campaigns.

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