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Snow stability measurements

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ABSTRACT: Field measurements of snow stability provide the only direct evidence of snow stability except avalanche observation. In–situ snow stability measurements are reviewed. Field data on shear strength of weak layers and tensile strength of slabs are described, as well as the appropriate techniques to collect the data. An overview of presently applied snow stability tests (rutschblock, compression test etc.) is given. New possibilities to measure the mechanical properties (e.g. SnowMicroPen) relevant for assessing avalanche danger are discussed.

KEYWORDS: snow avalanche, avalanche formation, snow mechanical properties, snow strength, snow stability

1. Introduction

The following paper provides a short review on snow stability measurements including tests in study sites and avalanche starting zones. Snow stability measurements such as the shear frame test or the rutschblock test provide the only direct information on the state of the snowpack. Assessing snowpack stability is the key to avalanche forecasting (Schweizer et al., 1998). Meteorological data alone is insufficient for assessing avalanche danger (Schweizer and Föhn, 1996). Besides stability tests, observations on avalanche activity represent the other type of relevant data for danger assessment. Both, avalanche activity and stability tests are so-called low entropy information (LaChapelle, 1980) or Class I data (McClung and Schaerer, 1993, p. 125). Measuring snow stability is difficult: Prevailing avalanche danger may hinder data collection; stability may vary within hours, spatial variability may limit extrapolation of results; measurement techniques may bias results; test results on snow stability may not be sensitive and/or specific. However, as Monty Atwater has pointed out (Tremper, 2001), there is no easy way around the above obstacles, since avalanches cannot readily be subdivided, reconstructed or reduced to laboratory scale, but are best observed in their native habitat.

If studying snow stability, we should know the essential factors for avalanche formation. The recipe is - in simplified form (Fredston and Fesler, 1988): steep terrain, a slab sitting on top of a weak layer or interface, a critical balance between the stress acting on and the strength of the weak layer or interface and finally a trigger to tip the balance. This is essentially a strength of material approach. The failure of a snow slope can also be considered from a fractural mechanical point of view. For a comprehensive model of avalanche release both views probably need to be combined together with a stochastic element for fracture initiation at the microscale (Fig. 1). It seems clear that dry-snow slab avalanche release starts with shear fracture at the weak interface followed by tensile fracture just before the slab is fully detached (leading to the crown fracture). Accordingly, much of the focus in this paper is on shear strength properties.

Following the strength of materials approach weak layer or interface properties and slab properties should be measured. Combining the two reveals stability as the ratio of strength over stress. Stability indices have successfully been applied and e.g. Föhn (1987*a*) has proposed the stability index *S*' for skier triggering:

$$S' = \frac{\tau_s}{\tau_g + \Delta\tau} \qquad [1]$$

where τ_s: shear strength of weak layer or interface, τ_g: shear stress on weak layer/interface due to gravity acting on the overlying slab, and $\Delta\tau$: additional shear stress due to the load of the skier. Both, weak layer strength and slab properties, need to be assessed for stability evaluation. Most stability tests implicitly involve both properties. The fracture mechanics approach is in its infancy, but it is promising and should be followed in the future as well. As the paper is a summary of an invited talk, we do not tend to give a complete review or a complete list of references. We are rather selective but believe that the provided references steer the more interested reader to relevant literature.

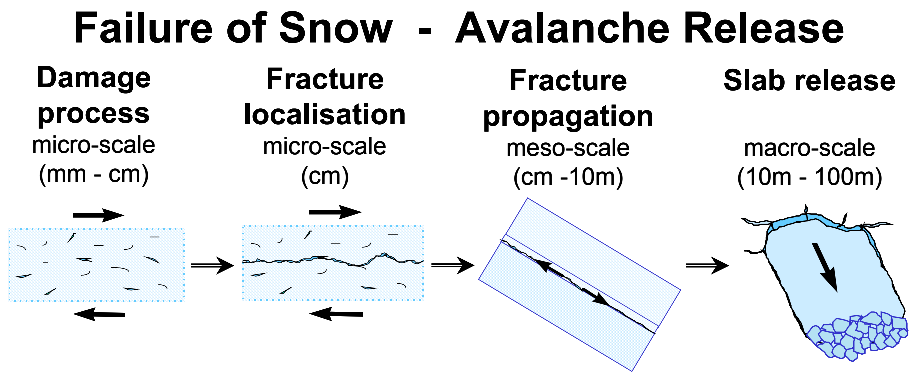

Figure 1. *Schematic of processes involved in dry snow slab avalanche release.*

2. Strength measurements

2.1. *Shear strength*

Shear strength of weak layers is best measured with the shear frame. The rotary shear vane is more suited for measuring the shear strength of homogeneous snow layers (Brun and Rey, 1987). The shear frame was introduced by the Swiss André Roch and first described by deQuervain (1950). The technique has been much refined by Jamieson (1995) who has done detailed field studies. Shear frame tests can be done in avalanche starting zones, or in level or modestly steep study sites. Stability indices extrapolated to slopes from measurements in level study plots have been proven to be predictive for slope stability (Jamieson and Johnston, 1993, 1995). Föhn (1993) provided a first overview on shear strength values of weak layers. Föhn et al. (1998) compiled shear strength data and show, by instrumenting a shear frame, that during a shear frame test the usual loading rate (rapid) results in brittle fracture. For details on the measurement technique the reader is referred to Jamieson and Johnston (2001). At present, Jamieson and Johnston (2001) provide the most comprehensive set of strength values of weak layers (Fig. 2).

The weak layer strength data in Figure 2 is shown in relation to density, and grouped according to grain type. Since layers of surface hoar, one of the most frequent grain type in skier triggered avalanches (Schweizer and Jamieson, 2001), are always too thin for density sampling, no data for surface hoar are included in Figure 2. Group I includes precipitation particles, decomposing and fragmented particles and rounded grains (so-called non-persistent grain types). Group II consists of faceted crystals and depth hoar; these grains types are so-called persistent grain types, since layers of these grain types and of surface hoar represent weaknesses that can persist in the snowpack for weeks, and sometimes even for months. For both groups a relation for the dependence on density is given. In general, the dependence of tensile and shear strength on density is non-linear. Good fits of strength to density have been obtained if relative density, ρ_{snow}/ρ_{ice}, is considered (Perla et al. 1982). For a given density of 100-250 kg m^{-3}, Group II grain forms have substantially lower shear strength than Group I grain forms. The regressions in Figure 2 can be used to estimate the shear strength for some common grain forms of weak snowpack layers, and the Group I regression was used by Conway and Wilbour (2001) to predict new snow instability in a maritime climate regime.

Relative density is generally used to describe the properties of foams (Gibson and Ashby, 1997). Kirchner et al. (2001) proposed – as others previously - to consider snow as a foam, and have accordingly used relative density. Based on a simple foam model and geometric relations, they proposed that yield stress or strength of snow should depend on relative density raised to the power 3/2, whereas Conway and Wilbour (2001) use the same arguments and propose the power to be 2.

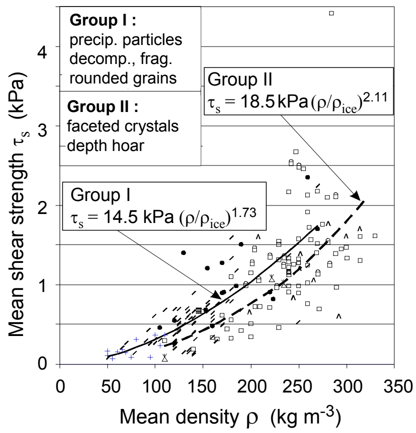

Figure 2. *Shear strength for weak snow layers by density and grain form. (after Jamieson and Johnston, 2001; reprinted from Annals of Glaciology with permission of the International Glaciological Society)*

The shear strength of surface hoar layers is lowest of the persistent grain types. Based on the data provided by Föhn et al. (1998), the shear strength of buried surface hoar layers was found to be 1.1±0.6 kPa, measured on average 26 days after burial (N=65). Shear strength values shortly after burial are significantly lower. Jamieson and Schweizer (2000) report the shear strength over time for 19 buried surface hoar layers. The first measurement was on average 7-8 days after burial and revealed an average shear strength of τ_s = 0.6±0.35 kPa for a crystal size of 5-10 mm. Shear strength depends on age after burial and initial maximum crystal size.

Measuring shear strength of weak layers in a study plot at regular intervals reveals how layers gain strength with time. Figure 3 is an example for three buried surface hoar layers. Typical strength increase was about 0.1 kPa/day. Recently, Chalmers (2001) has shown that shear strength of buried surface hoar layers is most affected by the load overlying a layer of buried surface hoar. He developed a model that predicts shear strength of buried surface hoar layers based on a number of variables: age of the layer, load, slab thickness, snow depth, weak layer thickness, weak layer temperature, crystal size and temperature gradient across the layer. The conceptual model on how surface hoar layers gain strength by Jamieson and Schweizer (2000) assumes that the load of the overlying slab pushes the surface hoar crystals into the adjacent layers leading to an increase in bonding, and a visible decrease in layer thickness.

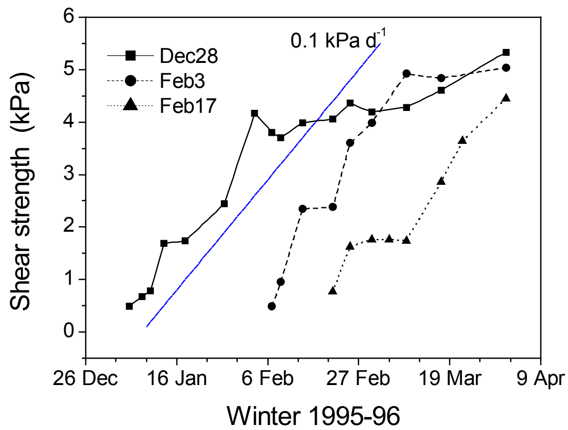

Figure 3: *Strength changes of three surface hoar layers. Dates indicate day of burial at Mt. Fidelity (Columbia Mountains, Canada). Straight line indicates average rate of strength increase: about 0.1 kPa* d^{-1}.

Shear frame test data from level study plots can be used to calculate a skier stability index extrapolated to a standard 38° slope. Jamieson and Johnston (1998) have proven that this stability index is a good indicator of instability for skier triggered slab avalanches, provided some refinements are introduced in regard to the original formulation by Föhn (1987*a*). Figure 4 shows that for a skier stability index $S_K < 1$ skier triggering is likely, that in a intermediate range $1 < S_k < 1.5$ skier triggering is possible, and that for values $S_k > 1.5$ skier triggering becomes unlikely. The stability index does not work well for natural avalanches suggesting that a simple stress criterion is not applicable for natural avalanche release.

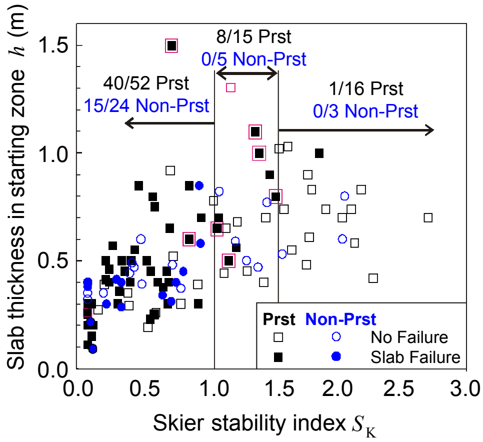

Figure 4 : *Slab thickness in starting zones, h, and skier stability index, S_K, for skier tested avalanche slopes: 83 persistent slabs (square symbols), 32 non-persistent slabs (circular symbols). Slabs that failed are marked with filled symbols and slabs that did not fail are marked with unfilled symbols (after Jamieson and Johnson, 1998; reprinted from the Annals of Glaciology with permission of the International Glaciological Society).*

2.2. *Tensile strength*

Tensile strength is a slab property. It mainly influences avalanche size since it contributes to the peripheral strength of a slab and correlates to slab stiffness. Jamieson and Johnston (1990) have measured tensile strength and found that the width of unconfined slabs is related to tensile strength: the stronger the slab, the larger the avalanche size (Jamieson and Johnston, 1992). Measuring tensile strength is more delicate than shear strength. Figure 5 shows the dependence of tensile strength on density and grain form. Again a fit for the two groups of grain types (same as above) is given using relative density as independent variable

$$\sigma = A\left(\frac{\rho_{snow}}{\rho_{ice}}\right)^{\alpha} . \qquad [2]$$

suggesting that snow could be characterized for a certain density range as foam. Jamieson and Johnston (1990) found that the layers with grains of group II (faceted crystals) had substantially lower strength than the layers with grains of group I (precipitations particles, decomposing and fragmented particles, rounded grains). The constants in eq. 2 were determined for Group I: A_I = 79.7 kPa, and α_I = 2.39; and for Group II: A_{II} = 58.3 kPa, and α_{II} = 2.65. Tensile strength is accordingly about 50-100% larger than shear strength for a given density and grain type.

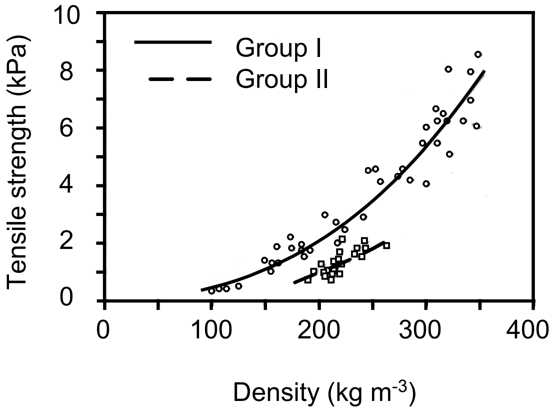

Figure 5: *Dependence of tensile strength on density and grain form. (after Jamieson and Johnston, 1990; reprinted from the Journal of Glaciology with permission of the International Glaciological Society)*

Tensile strength can as well be determined with the cantilever beam test (Perla, 1969; Mears, 1998). The beam number as proposed by Perla (1969) can be considered an index of the flexural strength of the overlying slab. Since stress distribution is likely inhomogeneous it cannot directly be related to tensile strength. Johnson (2000) improved the technique for the cantilever beam test such that the undercut is made at constant rate. He gives the dependency of the beam number on density. These beam number data can be fitted to a similar equation as eq. 2 with $A \approx 1$ kPa, and $\alpha \approx 3.4$, suggesting that the stress distribution across the beam is in fact inhomogeneous.

3. Stability tests

In-situ snow slope stability tests usually involve isolating a snow block including a weak layer and loading the block at given steps. Therefore slab properties and weak layer properties are tested in combination. All common tests are essentially dynamic tests and try to reproduce to a certain degree the loading by a skier or snowboarder. The rate of loading is fast and usually brittle fracture results. Stability tests are most indicative on slopes, but can be done in gentler terrain to avoid exposure to avalanche danger. It is suggested that the larger is the test area, the more reliable is the test result. The most commonly used tests are the rutschblock test (Fig. 6), introduced by Föhn (1987*b*) and the compression test (Jamieson, 1999). A variation of the compression test is the stuffblock test (Birkeland and Johnson, 1999) in which the load is more quantifiable but applied in larger steps possibly resulting in a slightly less sensitive test (Fig. 6). As for the case of the shear frame test (Fig. 4), test results can be compared to avalanche activity on surrounding slopes to assess the validity of the stability test. This has been shown for the case of the rutschblock test (Föhn, 1987*b*; Jamieson and Johnston, 1995) and for the compression test (Jamieson, 1999). Figure 7 shows the results for the compression test. The frequency of skier triggering clearly decreases as the average compression score increases. While the decreasing trend is encouraging, it should be noted that about 10% of the slabs with hard compression scores were skier triggered, clearly showing the limitation of such stability tests. When assessing snow stability with stability tests, not too much confidence should be placed on any single point observation of the snowpack.

Figure 6: *Rutschblock test (left), compression test (center) and stuffblock test (right).*

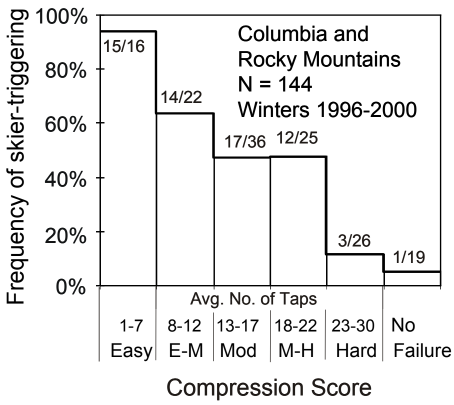

Figure 7: *Results of compression tests on avalanche slopes where 144 slabs were ski-tested. Sixty-two of these were triggered. For each compression score group the number of slopes triggered out of the total number of slopes tested at this score is given: e.g. 14/22 (after Jamieson, 1999).*

The reason for the fact that stability tests occasionally fail to indicate instability is likely the variable nature of the snowpack. Disorder at several scales within the snowpack seems obvious. In particular meteorological conditions during snowfall events contribute to variability. There are several possibilities for variability in view of avalanche formation. There can be variability of the slab, e.g. varying thickness, or variability of the weak layer. The weak layer might not exist at certain places, or the strength of the weak layer at places where it exists might vary. For any case the scale of the variability is unknown so far. The scale that is suggested to be important for avalanche release is 0.1 to 10 m (Schweizer, 1999). This is the scale of the size of a critical initial fracture that is necessary to drive fracture propagation prior to slab release. It is assumed that the shorter length is critical during rapid loading by a skier (McClung and Schweizer, 1999). In-situ measurements of the deformation induced by a skier (Schweizer and Camponovo, 2001), observation on skier triggering and laboratory measurements on the fracture toughness of snow (Kirchner et al., 2002*a*,*b*) indicate that for skier triggering the critical size for self propagating fracture is likely less than 1 m^2. We assume that the amount of variability will depend on the type of weak layer since we expect certain layers to be relatively continuous (e.g. crusts), whereas others (surface hoar) are more prone to erosion by wind while on the surface. In addition, we suspect that already conditions of weak layer formation can be decisive. Again crusts or near surface faceting might exist more widely, whereas surface hoar is typically limited to certain terrain features or elevations bands. Finally, when the scales are clear, it is still unclear what the effect of variability is on avalanche formation. High spatial variability might offer points of fracture initiation, but might also limit fracture propagation. On the other hand low variability seems favourable for fracture propagation, but in this case failure initiation obviously will depend on the level of stability. Intermediate stability with a certain degree of variability seems to be most critical in view of skier triggering, i.e. the risk of triggering is difficult to assess which might suggest special caution.

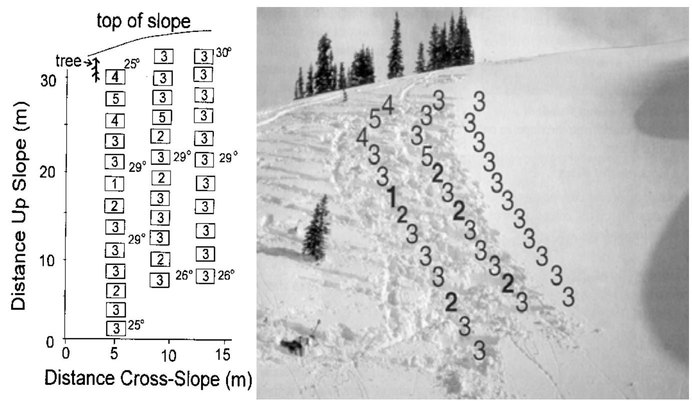

Figure 8: *On this small slope, 36 rutschblock tests were performed within a few hours. (The rutschblock scores on the right in the photo were obtained after the photo was taken.). Schematic on the left shows slope angle and spacing of tests (from Jamieson, 1995; 2000)*

In the past, several field studies tried to explore spatial variability of the snowpack. For a summary, see Schweizer (1999). None of these studies, mainly performed on small slopes, has proven dramatic changes in stability from one meter to the other. However, substantial variation was found. The results were variable, but not completely random. As an example a result by Jamieson (1995) is shown in Figure 8. Jamieson (1995) states that by avoiding obviously disturbed sites, most rutschblock scores can be expected to be within ±1 step of the slope median.

Presently, several studies are under way that try to quantify snowpack variability at different scales (Haegeli and McClung, 2001; Kronholm et al., 2003; Landry, 2002; Stewart, 2002). Preliminary results are in line with the outline of the problem as given above.

4. Other snowpack properties

Stability tests are frequently done after snow stratification has been recorded. The classical snow profile allows to analyse the stability based on the differences in layer properties and the overall consolidation of the snowpack. According rules have been derived and grain size and layer hardness seem to be most indicative, besides rutschblock score, if available (Schweizer and Wiesinger, 2001). Large property differences in general between adjacent layers suggest instability. Comparing snow profiles taken on slopes that were skier triggered to profiles from slopes that were skied but not triggered, clearly shows that grain size and hardness difference are indicators of weaknesses in the snowpack (Figure 9) (Schweizer and Jamieson, 2003).

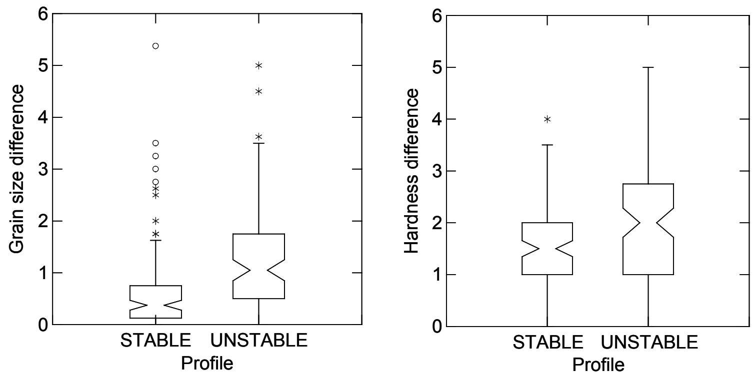

Figure 9: *Comparison between 95 unstable (skier triggered) and 107 stable profiles (from slopes skied but not triggered). Differences in grain size (H-Test, p<0.001) (left) and hardness (H-test, p=0.002) (right) between weak layer and adjacent layer, or between layers adjacent to weak interface is shown (from Schweizer and Jamieson, 2003; reproduced from Cold Regions Science and Technology with permission of Elsevier Science).*

Obviously, grain size and hardness differences are only indicators. The number and size of bonds per volume within a layer, or more likely between two layers is relevant. Soft layers of large faceted grains form likely layers with few bonds per volume and accordingly should also have few bonds to an adjacent layer.

Snowpack properties in general and characteristics of skier-triggered slab avalanches can be found in Schweizer and Jamieson (2001).

5. Alternative and new measurement techniques

As avalanche release involves brittle fracture, and a size effect, i.e. the critical size for self propagating fractures, it seems obvious that fracture mechanical properties should play a significant role. The key parameter in fracture mechanics is the fracture toughness K. It is usually determined in a cantilever beam geometry. Kirchner et al. (2000) have first measured fracture toughness of snow in tension, K_{Ic}. Subsequent laboratory measurements suggest that snow is one of the most brittle materials known to man. Typical values of K_{Ic} and K_{IIc} are of the order of 500 Pa $m^{1/2}$ for snow of density $\rho \approx 200$ kg m^{-3}, and consisting of mainly fragmented and decomposing particles and small rounded grains, i.e. for a typical slab layer (Kirchner et al., 2002a,b). So far only samples from homogeneous layers were tested, but the cut was made parallel to natural snow layering. In the future layered samples will be studied. Interfacial fracture mechanics will provide the bases for analysing such measurements, and to relate them to snow stability.

The newly developed high resolution snow penetrometer, or SnowMicroPen, provides a new technique to quickly measure snow penetration resistance and gain information on snow stratigraphy without opening a snow pit (Johnson and Schneebeli, 1999; Schneebeli et al., 1999; Pielmeier et al., 2001). Preliminary results show that the signal is related to the snow texture and that texture differences can be detected that are likely potential weaknesses in the snowpack.

Other measurements techniques that to a certain degree provide information on snowpack properties useful for assessing snow stability are the FMCW radar and acoustic emission measurements. Both types of measurements could be used for the remote instrumentation of an avalanche slope to closely monitor the snowpack development prior to a natural avalanche release.

6. Discussion and conclusions

The application of any in-situ snow stability measurement to be performed on avalanche slopes is limited by the prevailing avalanche danger. Limited accessibility to avalanche terrain often prevents snow stability measurements that can be used operationally. Accordingly, consistent and continuous measurements during most of the winter are needed so that at least an extrapolation based on recent snowpack information is possible. The gap in spatial and temporal resolution should be filled with the help of numerical snow cover models that include stability information (Durand et al., 1999; Sokratov et al., 2002).

So far all methods are destructive which prevents to a certain degree to study the temporal evolution at a single one location. In general, it must be stated that, besides the newly developed SnowMicroPen, all methods are relatively crude, partly insufficient, but approved and reliable. Presently, there is no precise measurement – in the strict sense – of snow stability.

On the other hand, the field studies on snow stability have substantially increased our knowledge on avalanche formation. Weak layer strength can reliable be measured with the shear frame test and used to calculate stability indices with predictive power for skier triggering. Weak layer strength development can successfully be modelled. Similarly stability tests provide invaluable direct information used by all avalanche professionals and in particular by all warning services. In-situ observation of the microstructure by microphotography suggests that bonding between adjacent layers is crucial for stability assessment. Interface fractures are likely not the exception but the rule. In the future, more sophisticated measurements will be needed so that the input parameters can be provided for a slab avalanche model that starts with damage at the microscale and ends with fracture propagation and slab release at the macroscale.

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