STRENGTH COMPARISONS BETWEEN AVALANCHE AND NON-AVALANCHE SNOWPACKS[1]

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Abstract -- To help alleviate difficulties in experimental testing of snow strength, stresses creating actual slab avalanches are evaluated using a simple model of avalanche mechanics. Fracture-line profiles of slab avalanches show measured snow properties of a system that has responded to applied stresses by fracturing. For example, shear failure occurs within a weak zone above the bed surface and tensile failure occurs at the crown wall of the slab-group.

When compared with the layered structure of stable snowpacks, the potential for these strength estimates as forecasting tools emerges. Tensile stresses calculated from fracture-line profiles emulate actual tensile strengths within the slab-group and appear greater than tensile stresses occurring in potential slab-groups of stable profiles. Limitations of the data and the applied mechanical model are illuminated. Improvements are suggested for field observations and experimental techniques.

INTRODUCTION

The mechanical strength of alpine snow plays an integral role in the formation of slab avalanches. Unfortunately, the mechanical properties of snow are complex and poorly understood. Because it is a granular material applications of soil mechanics have been attempted (e.g., Bader and others, 1939). Also theories from ice mechanics (e.g., Mellor, 1968) have been used to model the solid fabric of snow. In reality, snow is a highly compressible, granular material coexisting in its solid, liquid, and gas phases. It displays viscous, elastic, and plastic responses to stress which depend on snow temperature, density, grain type and size. The subsequent rheological models and constitutive equations have been either too simple to be realistic and/or too complex to employ towards practical problems.

Collecting experimental evidence about mechanical properties is hampered by mechanical and thermodynamical instability of the delicate snow fabric. This is especially true for the low snow densities (less than 250 kg/m^3) encountered in alpine snowpacks. In addition, in-situ instruments must survive severe mountain storms and the creeping and avalanching snow they attempt to measure.

What little data that are available concentrate on brittle strength measurements. Unfortunately, it is not clear whether the stresses creating slab avalanches are of the proper duration or sufficient magnitude to impose brittle failure. Narita (1983) observed three types of fracturing occurring in snow under tensile stress, one brittle and two ductile. Gubler (1977) suggests that slab avalanching is a series of ductile failures based on the calculated strain rates of explosives used to initiate avalanching. He then concludes that strength values obtained from brittle tests are inaccurate estimates of the mechanical properties relevant to avalanches.

SNOWPIT PROFILES

Because of these difficulties and the questionable usefulness of available strength measurements, the use of fracture-line profiles (from snowpits dug near the crown region of actual slab avalanches) is proposed to disentangle the existing snow mechanical theories and observations. Fracture-line profiles provide physical measurements of snowpacks that responded to applied stresses by fracturing. Most observations are acquired within 24 hours of avalanching and are assumed to be representative of conditions at failure.

All fracture-line studies of actual slab avalanches have shown a cohesive slab-group sliding on a smooth bed surface. Because the crown fracture within the slab-group shows a nearly 90° orientation with the bed surface (Perla, 1969) it appears that this failure occurred under uniaxial tension. A weak, basal layer (either a finitely thick layer of unconsolidated snow, or poor adhesion between the slab-group and bed surface) is also observed and shear failure is expected here.

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A collection of over 800 snowpit profiles were acquired from mountainous areas throughout the world reflecting a variety of snow climates. Of these, only 78 were complete profiles of actual avalanches. That is, they contained measurements of density, temperature, hardness, grain type and grain size for each observed layer, and the exposed bed surface was clearly marked. A group of stable profiles (from snowpits dug at or near starting zones of avalanche paths which did not slide with the observed snowpack) were also chosen from the original collection. The potential slab structure was identified in these profiles using simple shear tests to locate planes of easiest shear. Measurements from both data groups (from fracture-line and stable profiles) were quantified and used in a simple model of slab avalanching so that the stress regime could be compared between avalanching and non-avalanching snowpacks.

MECHANICAL REQUIREMENTS FOR AVALANCHING

The mechanical model used for this investigation was first suggested by Perla (1971) and requires failure to originate in the shear zone. Here the formation of a basal slip surface allows slope-parallel tensile stresses to build up in the slab-group. McClung (1979b) has since modified this approach by describing the basal layer as a propagating shear band. Ferguson (1984c) then adapted the model to incorporate the physical characteristics of observed slab structures and utilize snowpit data.

Full development of the model can be found in the aforementioned publications as well as Palmer and Rice (1973) and McClung (1981) so will not be repeated here. However, a brief summary is in order. Figure 1 shows a schematic view of this model. A slab of finite thickness overlies a thin, weak, basal layer imparting a shear load and a normal load on the weak-layer. a. Before avalanching the material in the weak-layer is of sufficient strength to balanche the slab's load and the snow remains in place. b. If the weak-layer is perturbed (e.g., by skiers or explosives) it loses strength within a specified shear band whose length is proportional to the perturbed area. c. If the shear band strength falls below the slab's load a stress imbalance is created, and if the perturbed area is large enough (that is, it has reached a critical length) then the resulting stress imbalance may be sufficient to drive the growth of the shear band. This all depends upon the material properties of the slab-group and the weak-layer as well as the existing load conditions. When this happens the basal pinning of the slab-group is undermined and tensile stresses are built up in the slab.
d. Once these tensile stresses overcome the strength of the slab-group, tensile fracturing and avalanching may occur. If tensile failure occurs before critical shear band length is reached then the driving stresses for shear band propagation would be eliminated and it would not grow. Therefore, by calculating the tensile stresses at the tip of the critical shear band lengths, an index of tensile strength may be determined, most likely reflecting the minimum strengths possible for each observed snowpack structure.

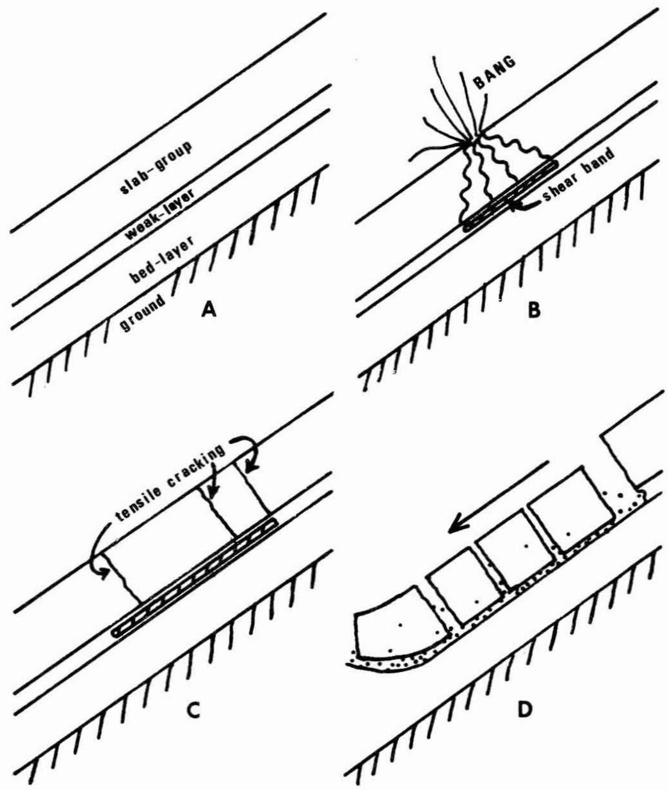


Figure 1. -- Schematic view of the progressive slip model of slab avalanching. a. Slab structure before perturbation. b. Shear band develops in the weak-layer. c. Tensile fractures appear. d. Slab avalanching occurs.

For every snowpack structure, there is a critical shear band length where the undermined slab imparts enough load to overcome the strength of the weakened shear band and shear band propagation proceeds. Data from each snowpit profile was used to evaluate the critical length of a shear band given its observed snowpack configuration. These lengths varied from 1 to 20 meters with an average of 6.4 meters. This seems to agree with field experience. For example, sometimes only an area the size of a quick ski turn is enough to initiate widespread shear failure. Other times the combined area perturbed by several skiers is required before shear propagation proceeds.

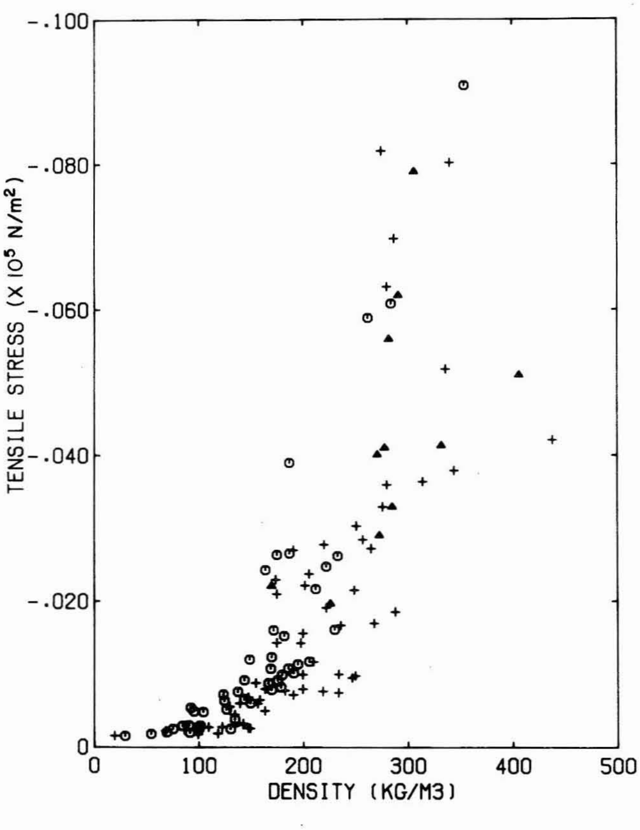
TENSILE STRENGTH

Tensile stress created at the upslope boundary of these critical shear band lengths showed principle directions oriented $15^{o} \pm 7^{o}$ to the snow layering. This is in close agreement with observation. As the shear band extends beyond its critical value, the principle directions may rotate even closer to layer parallel. In fact, the shear band may propagate far beyond its critical boundary and significantly greater tensile stresses can build up in the slab before they actually overcome the slab's strength. Local stress concentrations (e.g., convex areas, ski tracks, existing cracks, rocks or vegetation, etc.) also will influence these values. Therefore, tensile stresses calculated at the tip of the shear band when it is at its critical length only provide an index, or minimum boundary of tensile strengths existing in natural slabs.

These data are shown plotted against density in figure 2. The distinction between hard-slabs and soft-slabs was introduced because field experience shows that the two slab types respond to applied stresses differently. In addition a quantitative analysis (Ferguson, 1984b) showed these two types characterized by entirely different physical parameters. Slab avalanche classification is a subjective observation made at, or near, the time of avalanching and is based on U.S. Forest Service classifications (Perla and Martinelli, 1976). Two features of this plot are of interest: 1. Tensile stresses generated by this slab mechanical model appear only slightly higher for unstable snowpacks than stable snowpacks; and 2. Hard-slab avalanches show relatively low tensile stress values.

Although many of the tensile stresses generated in snowpacks that failed as slab avalanches seem higher than those potentially generated in stable snowpacks, the distinction is very slight. A previous study (Ferguson, 1984b) showed that stable snowpack structures are characterized by different physical features than unstable snowpack structures. Therefore, it may be expected that they would respond to applied stresses differently. Potential weak-layers in stable snows probably have the proper

Figure 2. -- Calculated tensile stress vs. density for soft-slabs(⊙), hard-slabs(▲), and stable snowpacks(+).



grain fabric to propagate shear disturbances (since they are located and identified with a shear test). However, there may be terrain features that inhibit propagation (like protruding rocks or trees), or the weakness is not consistent (like isolated pockets of surface hoar or graupel). An additional, spatial distribution parameter to describe the cross-slope variability of snowpack features would help to determine the effect of constraints from terrain and snow structure.

Perhaps the similarity in calculated stresses is because there is not enough load from the slab-group, or the slab-group is strong and can withstand the generated stresses in a stable snowpack structure. It may be appropriate to weight the strongest layers of the slab-group. For instance, rain crusts are typically an order of magnitude stronger than other snow types. Their densities are usually not recorded in the field because of sampling difficulties, but because of the high refrozen water content, may approach that of glacier ice (860 kg/m^3). Indeed, over 45% of the stable profiles had some kind of melt-freeze crust. Most of these (42%) were rain crusts with average thicknesses near 4 ± 3.8 cm. This may be compared to the 36% of unstable profiles whose slab-groups contained melt-freeze crusts. Most of these (40%) were thin (2.7 ± 1.6 cm), sun crusts.

The relatively low tensile stresses generated in hard-slab avalanches may reflect some interesting characteristics suggested by Gubler (1978). He visualized slab avalanches initiating with a ductile failure. This then propagates through the snowcover by brittle fracturing. He hypothesized that a wide distribution of strengths within chains of bonded grains (fundamental units) implies a high ratio of ductile to brittle strength within the material. This means that it would be difficult for fractures to initiate naturally, but once triggered, rapid, wide-spread fracturing would occur.

Tensile strength measurements of natural snows are used to investigate the distribution of fundamental unit strengths. Figure 3 illustrates tensile strength as a function of density from measurements produced by centrifugal tests on 100 and 500 cc snow samples (Bucher, 1958; Bader 1962; McCabe and Smith, 1978; Keeler, 1969; Sommerfeld, 1971; Ramsier, 1963; and Narita, 1980). Included are the bending beam tests of Perla (1969) and McClung's rolling cart tests (1974) who use larger sample sizes.

Hard-slab avalanches in the fracture-line profile data set have densities between 190 and 400 kg/m^3. The largest variation of strengths illustrated in figure 3 occur between a similar density range. If Gubler's hypothesis were true, this would imply that these densities have a high ratio of ductile to brittle strengths and naturally occurring hard-slab avalanches become rare, whereas triggered hard-slabs could be massive. Indeed, hard-slab avalanches often show these characteristics. For example, avalanche forecasters at Lake Louise in the Canadian Rockies complain of persistent unstable hard-slab snowpacks, with very weak shear zones. Since there is little natural activity, it is difficult to explain the potential hazard to backcountry travelers. However, once the proper trigger is applied to initiate tensile failure, a swift fracture sequence follows.

A 1982 avalanche in the Kenai mountains of Alaska (Fesler, 1983) is an extreme example of a

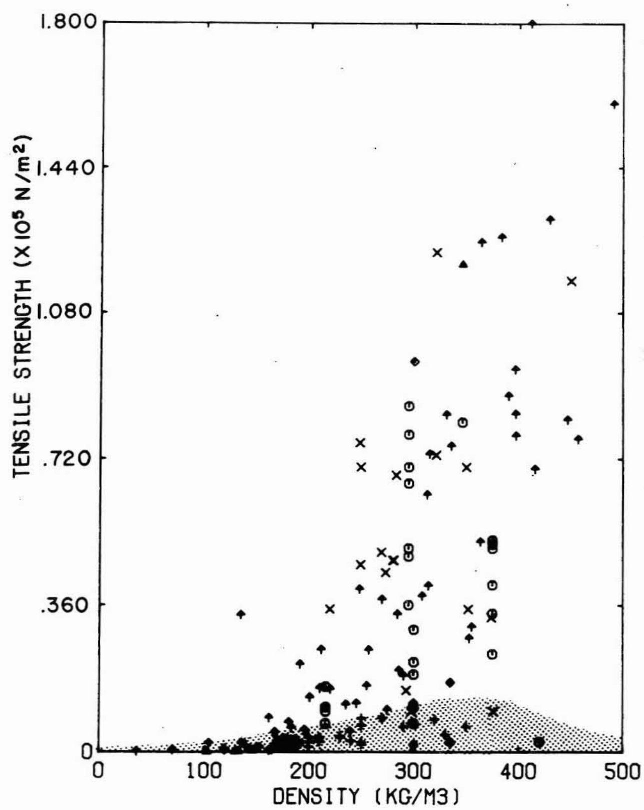


Figure 3. -- Experimentally measured strength vs. density from centrifugal tests (Bucher, ⊙ ; Martinelli, ↑ ; and others, X), rolling carts (McClung, +), and bending beams (Perla, ▲). Calculated tensile stress from fracture-line profiles as a function of density is shown in the shaded region.

large hard-slab avalanche waiting for the proper trigger. Although the slab-group was too hard to obtain density measurements, a reasonable estimate may be in the range of 450 kg/m^3. The crown face was measured at least 6 meters high, stretching nearly 370 meters across the slope and the weak-layer was a thin, non-descript discontinuity. A massive cornice broke off from above onto the slope. Rapid brittle fracturing probably ensued with the resultant avalanche.

These results imply that a progressive slip model may not be sufficient to estimate tensile strengths in hard-slab avalanches. Measurements of the areal extent of hard-slab avalanches would help to estimate their actual tensile loads. These data are rare.

Another contribution to these low tensile values for hard-slab avalanches may be in the structure of the slab-group itself. Field experience shows that wind deposited snow layers (the most common hard-slab origin) often have many shear planes between the separate layers built by slight wind shifts or temperature changes during the storm. The existence of these shear planes makes a more complicated transfer of load to the basal layer and may in fact increase the build-up of tensile stress in the slab-group. Knowing more about slipping between snow-snow or snow-ice boundaries would help to determine the magnitude of this effect. (Most snow friction studies are concerned with sledding and skiing).

CONCLUSION

This study showed how snowpit profiles could be used to evaluate the stress regime of avalanching and non-avalanching snow. From the results one can visualize the limitations of this type of data. For instance, the site-specific, time-independent profile has a limited lifetime of operational use and is only representative of a small portion of the total avalanching area. A more detailed description of the terrain variations and the spatial distribution of snowpack structure would help. Also remote, continuous monitoring equipment of some more important snowpack features, like snow layering, would help improve the operational use of snowpit profiles, especially for avalanche forecasters who are far removed from their forecast area.

Another aspect of this study applied a simple mechanical model to the wide variety of snowpack conditions. The results showed the limitations of the model, especially when applied to potential hard-slab avalanches. In particular, this emphasized the discrepancies between ductile and brittle failure modes already alluded to in the experimental strength tests of snow. Because the transition between ductile and brittle failure occurs near the range of strain rates encountered in natural and artifically induced avalanching it may be that both types of failure play equally important roles in the balance of strength and stress on a sloping snowcover.

Clearly, more information about each, individual avalanche is necessary for these problems to be resolved. For instance, the areal extent of actual fracture boundaries, the position, type, and magnitude of the trigger, the terrain configuration, and the timing between triggering and fracturing would all help to more accurately determine the balance of stress and strength within the variety of naturally occuring, sloping snowpack structures. In addition, comparing measured tensile strengths of slab-groups to calculated stresses would be a fascinating extension of this analysis.

By quantifying and analyzing snowpit data in this way a better understanding of the role of snowpack structure in avalanching ensues. Useful application of the traditional snowpit observations is also benificial. This type of study offers a new perspective on the mechanical requirements for avalanching and helps to isolate those areas of observation that are deficient.

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