Between a slab and a hard layer:
Part 2 - The persistence of poorly bonded crusts in the Columbia Mountains

Bruce Jamieson
Dept. of Civil Engineering, Dept. of Geology and Geophysics
University of Calgary, Calgary, Alberta

Introduction

Wet layers on the snow surface that freeze become crusts, which are the bed surface for some slab avalanches (Fig. 1), a portion of which are difficult to forecast (Seligman, 1936, p. 308-310, 387). McClung and Schaerer (1993) stated that "weak bonding of snow above crusts is the most important feature of crusts with respect to avalanche formation." Because crusts are usually stiffer and harder than the overlying snow, they concentrate shear stress within the sloping snowpack and hence can contribute to shear failure at the upper boundary of the crust (Schweizer and Jamieson, 2001).

Fig. 1. Photo of an observer on 17 December 1996 at the crown of a natural dry slab avalanche in the North Columbia Mountains. The slab avalanche released in the facet layer on the rain crust that formed in mid November 1996.

The first article of this three-part series focused on the formation of poorly bonded crusts, mostly due to faceting above wet layers and crusts. This second article summarizes field data from the Columbia Mountains regarding the persistence of layers of facets and surface hoar above melt-freeze crusts. In this series, wet or moist surface layers that freeze are referred to as crusts although they may be classified as frozen wet grains (WGcl or WGmf), rain crusts (CRrc), sun crusts (CRsc) or melt-freeze crusts (CRmfc) according to observation guidelines (CAA, 2002).

Types of grains found on poorly bonded crusts

For natural avalanches in the Columbia Mountains, Haegeli and McClung (2003) reported that 17% released in facet layers on crusts, 6% released in surface hoar layers on crusts and 7% occurred on crusts without a weak crystal type reported on the crust.

From 1990 to 2004 in the Columbia Mountains, University of Calgary avalanche researchers and collaborators working mostly near Blue River and Rogers Pass have observed 335 detailed profiles near dry slab avalanches and "whumpfs"— where each whumpf is a fracture in a weak layer under a snow slab that did not release an avalanche (Johnson and others, 2001). The bed surface of 70 of these avalanches (including whumpfs) had crusts as the bed surface, implying the failure occurred in the overlying weak layer, and likely at the interface of the crust and weak layer where shear stress was concentrated. The primary grain types for the weak layers were: 39 layers of faceted crystals (FC), 23 of surface hoar (SH), one of depth hoar (DH), three of rounded grains (RG), three of decomposing and fragmented particles (DF), and one of precipitation particles (PP). All three of the weak layers of rounded grains had facets as their secondary (less evident) grain type. Grouping these three layers with the other layers of facets, we see that 94%

of the weak layers included facets, depth hoar or surface hoar — the three grain types of weak layers known for their persistence in the snowpack (Jamieson and Johnston, 1992). This leaves four non-persistent weak layers: one of PP and three of DF particles. From weather records, the age of the PP and the three DF layers were 2, 2, 3 and 6 days on the day of the avalanche. Of the 39 facet-on-crust avalanches, the percentage of the facet layers less than 10 and 20 mm thick was 39% and 58%, respectively, indicating the importance of *thin* facet layers for slab avalanche release on crusts in the Columbia Mountains.

The age of layers that released slab avalanches on crusts is summarized in Figure 2 by grain type. Clearly, layers of facets or surface hoar on crusts remain potential failure layers on crusts much longer than layers of new snow forms or DF particles. The median and first and third quartiles of age were greater for facet layers on crusts that released avalanches than for surface hoar layers on crusts.

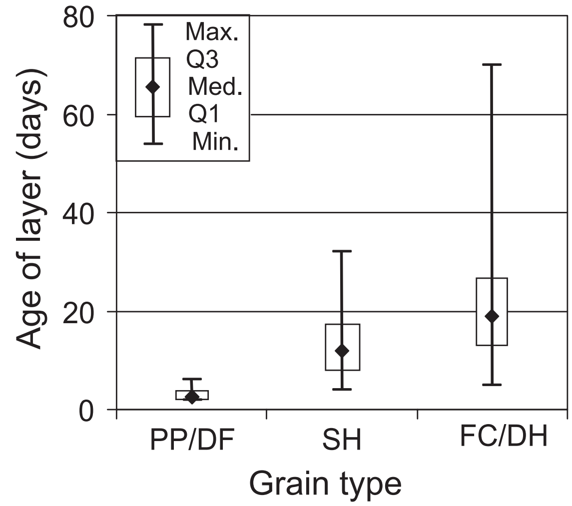

Fig. 2. Age of failure layers by grain type when they released dry slab avalanches on crusts. The filled diamond indicated the median age of the layers. The box includes the middle 50% of layer age and the whiskers indicate the full range of layer age. The layers of facets on crusts were often more persistent than layers surface hoar on crusts, both of which were often critical longer than layers of new snow forms (PP) and DF particles on crusts.

The size of surface hoar particles found on poorly bonded crusts

Since grain size as well as grain type likely affects the persistence of weak layers on crusts, let's look at particle size, starting with surface hoar layers on crusts that released avalanches. To graph the age of the layers, the burial date of the surface hoar layer must have been reported. This excluded some "patchy" surface hoar layers but included all widespread layers in the study areas. The average particle size ranged from 1 to 14 mm for these "dated" surface hoar layers on crusts when they released avalanches up to 32 days after burial. As shown in Figure 3, there is a trend for larger particles to be found in older failure layers. This is in spite of the tendency for the size of surface hoar particles manually taken from a particular layer to decrease over time (Jamieson and Schweizer, 2000). For layers with particles larger than 8 mm, the median age declines, perhaps because such large particles were less fragmented during extraction from the pit wall, as would be expected for recently buried layers. Where buried surface hoar overlies a crust, the surface hoar particles will

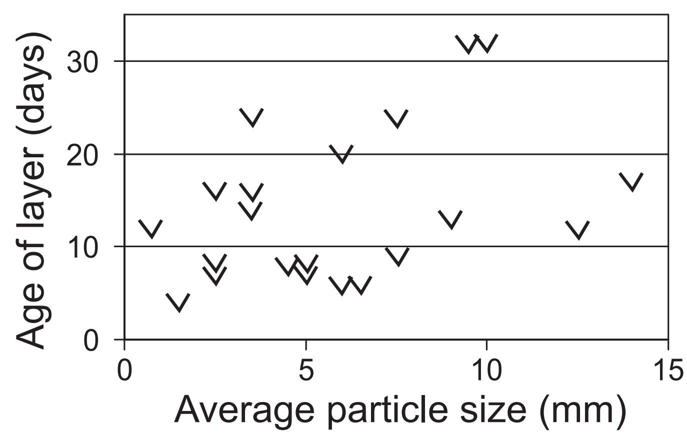

Fig.3. Age (since burial) and average particle size of 20 surface hoar layers on crusts when they released dry slab avalanches. Although there is considerable scatter, there is a general trend for the surface hoar particles to be larger in the older failure layers.

be slow to penetrate the crust, delaying an important mechanism for strength gain of a surface hoar layer (Jamieson and Schweizer, 2000).

To look at a larger dataset of surface hoar layers on crusts, Figure 4 shows the age and average particle size for layers that fractured consistently in compression tests (≤ 30 taps). The age varies widely for any size of particles; however, the median age increases from 14 to 19 days for particles from below 2 mm to 8 mm. For this range of average particle size, the first and third quartiles of age also increase with particle size.

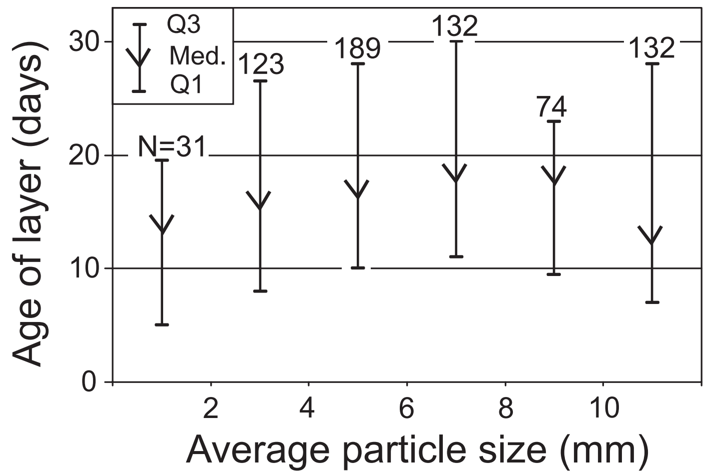

Fig. 4. Age of surface hoar layers (since burial) on crusts when they fracture consistently in compression tests (≤ 30 taps). For each range of particle size, e.g. > 2 mm and ≤ 4 mm, the whiskers shows the first and third quartiles of age and V indicates the median age. The number above the whisker indicates the number of layers each with unique location and/or date for which multiple compression tests yielded consistent fractures in the layer. The median age increases with average particle size up to 8 mm.

The size of faceted crystals on poorly bonded crusts

Consider layers of facets on crusts. The oldest layers that released avalanches in this study (Fig. 5) were older (> 60 days) than the oldest surface hoar layers on crusts (32 days, Fig. 3). This reflects the documented persistence of some facet layers that formed on November crusts in the Columbia Mountains (Jamieson and others, 2001; Haegeli and McClung, 2003). Five of the failure layers consisted of rounded facets (Type FCmx) of average crystal size between 1.25 and 1.75 mm that had been buried for 13 to 22 days, showing the persistence of weak layers of rounded facets.

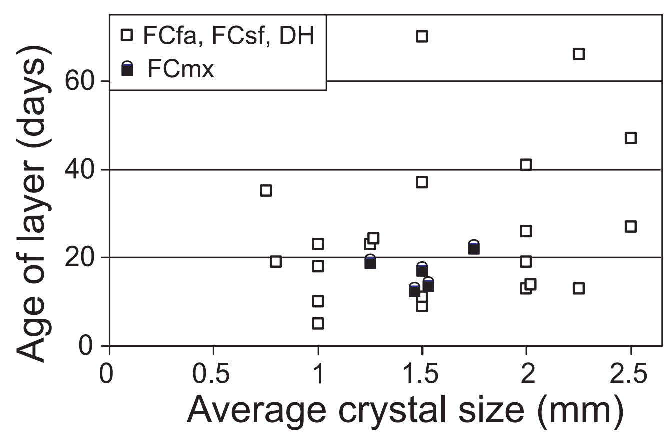

Fig. 5. Age and average crystal size of 26 layers of faceted crystals on crusts when released dry slab avalanches in the Columbia Mountains. The open squares represent layers of "sharp" facets (FCfa, FCsf) including one layer of depth hoar (DH). The filled symbols represent layers of rounded facets (FCmx). Although there is considerable scatter, the oldest failure layers tend to have larger crystals than younger failure layers.

To look at a larger dataset of facet layers that fractured on crusts, Figure 6 shows the age and average crystal size for layers that fractured consistently in compression tests. The median age of these layers increases to 67 days for crystals larger than 2.3 mm. The lack of data for facets (Type FCfa or FCsf) of average size less than or equal to 0.7 mm suggests their limited persistence as weak layers that fracture in compression tests. Since the bonds for small grains approach their maximum size much faster than larger grains (Colbeck, 1998), layers consisting of large grains are expected to gain strength much slower than layers of small grains. Also, there will often be fewer bonds per unit area at the failure interface because larger grains are typically farther apart than smaller grains. For average grain sizes less than 1.7 mm, Figure 6 shows little difference in the age of “sharp” facets compared to facets that exhibit signs of rounding (Type FCmx) when the layers fractured in compression tests.

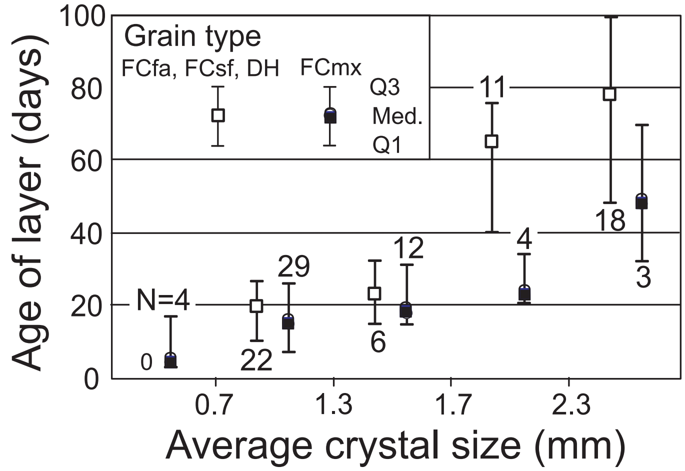

Fig. 6. Age of a facet layer (since burial) on crusts when the layer fractured consistently in compression tests. For each range of particle size, e.g. > 0.7 mm and ≤ 1.3 mm, the whiskers shows the first and third quartiles of age. The open squares represent the median age of layers of “sharp” facets (FCfa, FCsf) or depth hoar (DH). The filled symbols represent the median age of layers of rounded facets (FCmx). The number above or below the whisker indicates the number of layers each with unique location and/or date for which multiple compression tests yielded consistent fractures in the layer.

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Summary

In these Columbia Mountain observations, facets and surface hoar were found at the interfaces of many poorly bonded crusts, including almost all of those that released dry slab avalanches more than three days after the snow or surface hoar layer on the crust was buried. Although the size of particles from surface hoar layers that released slab avalanches on crusts were usually larger than for facet layers on crusts, the facet layers often remained potential failure layers for longer.

The persistence of weak layers of facets and of surface hoar on crusts increased with grain size. Based on limited data from dry slab avalanches, rounded facets up to 1.7 mm showed comparable persistence to sharp facets of similar size. In more abundant observations of fractures in compression tests, a similar trend was observed. Although rounding of facets is often considered evidence of improving bonding, an increase in stability is not apparent in these observations for layers of rounded facets less than 1.7 mm compared to sharp facets of similar size.

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