Study of Layered Snow under Shear and Tension

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ABSTRACT: Natural avalanche release involves the failure by both tension and shear. Clear illustration of this failure phenomenon individually or as a combination is not known till now. Lots of controversies still prevail whether initiation of failure is tensile or shear. It is necessary to evaluate the fracture properties of the snow pack for specific situations in order to characterize or map this behavior physically to the field conditions. Many studies and experiments on homogenous snow have been performed earlier to idealize this scenario. Real perspective of natural avalanche release phenomenon can be obtained by analyzing the layered snow under shear and tension loading. In this paper, such a process has been attempted experimentally in the cold laboratory under controlled conditions and in field under natural conditions. The comparison of the tensile and shear properties has been projected clearly with the help of experiments, which reveals the role of the respective properties in deciding the fracture behavior. As the experiments were conducted on layered snow, the characterization of interfacial failure stress under normal and shear loading conditions for different snow-snow interactions can be obtained. The load-displacement behavior for various snow-snow interfaces also interprets the phenomenal fracture mechanism of an avalanche.

Keywords:

KEYWORDS: tensile failure, shear failure, layered snow, interface, fine grained snow, Melt-Freeze snow

1. INTRODUCTION

A priori conditions that must exist for natural slab avalanche release is a weak layer within the snowpack McClung (1987). A thin/thick weak layer comprises the interfaces connecting with further strata of the snowpack. Interface can be defined by a distinguished feature of snow-grains constructed at either end of each layer due to effect of another layer. The grains at this interface changes due to micro and macro temperature conditions of adjacent snowpack layers. These interfaces strongly influence the physical and mechanical properties of the whole snowpack in a long run. The interfaces may be two dimensional (no thickness or thickness <1mm) or three dimensional (a very small thickness 2-5 mm may be involved) depending on the temperature conditions and hence constructing a two dimensional *interface* plane or an *interphase* introducing a small thickness at the interfaces. *Interphase* can be defined by an interface having some thickness. A *layer/interface/interphase* within snowpack is considered weak if it is weaker than adjacent snowpack layers. The weak snowpack layers were classified by Jamieson (1995) as non-persistent weak layers and persistent weak layers. He classified these layers on the basis of newly fallen snow which stabilize within a few days and depth hoar layers, providing a potential failure plane for avalanches. Persistent weak layers within the snowpack form due to metamorphic processes and can consist of three following snow crystals: surface hoar, facets and depth hoar.

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When a slab avalanche releases, failures occur on five surfaces. One in tension at the top of the slab constructing crown, two lateral shear failures on the sides of the slab constructing flanks, one compressive failure at the toe of the slab constructing stautchwall and a shear failure between the slab and the supporting superstratum (see fig. 1). In General, complete avalanche originates basically from failure under shear and tension. Bucher (1948) and Roch (1956) proposed that one of these fractures could be considered the primary rupture and other four following called secondary failures. He emphasized that the shear strength of weak layers in relation to the stress imposed by the overlying slab was the most important relationship determining the stability of snowpack on a slope.

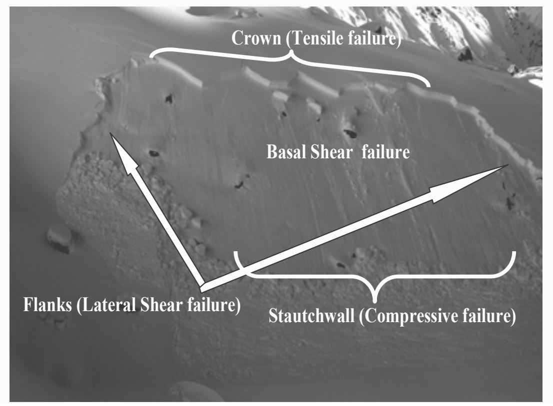


Figure 1: A typical slab avalanche on February 2, 2005 (near Patseo)

Prior to 1970, there was no consensus on the initial mode of failure occurring within the snowpack to start an avalanche. Haefeli (1963, 1967) believed that tensile fracture at the crown was the initial and most important failure. Bradley and Bowles (1967) worked on the lines of Roch and focused on compressive failure within a weak layer beneath the slab. Their work considered thick layers of depth hoar while Roch (1956) considered thinner weak layers. Sommerfeld (1979) argued that the initial fracture was tensile that started from a microcrack at the top of the snowpack. This microcrack could be either natural or caused by a skier. In his view, the tensile fracture starts at the surface and proceeds downward until a layer of low shear strength snow is encountered, further propagating the fracture along the layer of low shear strength. For such brittle fractures to occur either the applied load increases rapidly or high strain rates are present. Sommerfeld states that the vertical cracks dissipate the tensile stress in the snowpack leaving no stress to propagate shear fractures. Perla and LaChapelle (1970) made a compelling argument that the first failure in a slab occurred due to a loss of shear support. They argued, however, that the first fracture is a tensile crown fracture. In their theory, the basal failure is ductile leading to increased stress in the crown region followed by a brittle crown fracture that extends into the basal weak layer.

McClung (1981, 1987) focused on ductile shear failure of weak layer followed by shear fracture and propagation through the weak layer at the base of the slab and consequent tensile crown fracture. Gubler and Bader (1989) and Bader and Salm (1990) have also assumed that shear fracture occurs first.

Schweizer (1999) presented a complete review of dry snow avalanche release. He concluded that while the initial failure in the weak layer was most commonly accepted as a shear failure, it was quite plausible that the initial failure in the weak layer could be a compressive failure. All of the models he reviewed were of two-dimensional inclined snowpack with an assumed prior weakness existing in the homogenous layer.

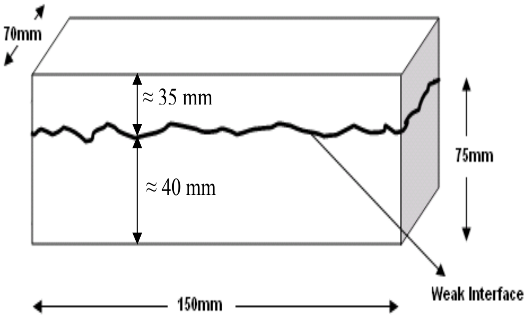
As stresses originating within the snowpack play a major role in determining the fracture behavior, it serves as an essential property in avalanche initiation mechanism. More research on evaluation of strength of homogenous snow in a snow pack were done till now. Gold (1956) and Jellinek (1959) made an attempt to evaluate the strength of snow in compression. Radke and Hobbs (1967) provided a relationship of strength with respect to the density variation in snow pack. Similar attempts in investigating the mechanical properties of snow were done by Keller and Weeks (1968). Mellor (1977) also classified the various engineering properties with respect to density of snow pack. Further, McClung (1979 a,b) evaluated the shear and tensile strength of the snow pack with the help of direct simple shear tests and few in-situ tensile strength tests. However, Sommerfeld (1980) classified the avalanche behavior based on strain rates and also studied the significant statistical interpretation of the snow strength. Bradely et. al. (1977) had undertaken investigation to evaluate the process of temperature Gradient metamorphism on the mechanical properties of snow. Kirchner (2002) in turn performed few tests on simple cantilever geometry of snow and determined the fracture criterion in mixed mode. He has also signified the role of fracture toughness in deciding the fracture behavior. All the above said work was done purely on homogenous snow.

As stated earlier, in this paper we evaluate the properties of layered snow which in turn is a great improvement over the earlier studies of homogenous snow. The significance of such study in layered snow is to interpret the experimental fracture behavior with the field avalanche initiation mechanism. Salm (1982) in his review states the failure criteria based on structure and fracture propagation with the help of mechanical properties of snow. In his work he has pointed out the importance of the properties of individual layers and the interfaces to understand mechanically the snow pack as a whole. However, Smith (1972) has worked on layered snow pack for the determination of elastic stresses in the layers. Further, very few studies on layered snow have been originated till date. We hope this study will form a significant milestone in characterizing the fracture behavior by determining interfacial failure stresses under tension and shear pertaining to layered snow.

Test geometry and sample preparation for layered snow

Experiments under controlled conditions in cold laboratory:

Snow samples collected from Patseo (3800m, m.s.l, $32^0$45'N and $77^0$15'E, Great Himalayan range), preserved at -20^0 C were used for sample preparation. Patseo, which encounters continental type of snow climate, faces extreme temperature conditions and hence snow remains dry for most of the winter period. Average minimum temperatures during winter in this region are generally -25^0 C and average maximum temperature goes upto -8^0 C. Due to low temperature conditions the formation of faceted grains, surface hoar and depth hoar grains is also common. The avalanches in this region are generally slab avalanche or air borne powder avalanche. These avalanches generally form due to weak layers persisting within the snow pack. These conditions hence justify the selection of location for collection of snow for preparation of layered snow samples. Cylindrical samples of 65 mm diameter and 150 mm height were chosen for tension tests and rectangular samples of 150 mm x 75 mm x 70 mm were chosen for shear tests. The samplers were filled with sieved snow (fine grained snow of grain size 0.5 mm to 1.0 mm) up to two third of its level in a view to accommodate the interface formation along the top surface. Six such samples were prepared for this experimental analysis. As a first step of sample preparation, all six samples were allowed to undergo aging for 24 hours. After this process, all the samples were subjected to melt-freeze cycle (i.e. at 0^0 C for 4 hours and back to -9^0 C) for four days successively. The significance of performing the melt freeze cycle in the sample is to establish an interface. The same procedure was also used by Srivastava et. al. (2004) to prepare the melt-freeze snow. Soon after the end of melt freeze cycle, the remaining unfilled part of the sampler was also filled with the sieved fine grained snow at -9º C. Further the snow samples were stored at -9^0 C for seven days to facilitate sintering process. Figure 2a and 2b depicts the rough sketch of a layered sample for shear test and tension test.



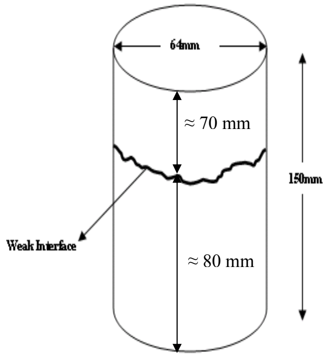


Figure. 2a: Layered sample for shear test
Figure. 2b.Layered sample for tension test

Experiments on natural field snow samples:

All field experiments were done at Patseo. Shear tests were done on the various interfaces found within the snowpack by cutting the snow bocks of size 150mm x 75mm x 70mm. A translucent profile of the snowpack taken on February 2006 is shown in figure 3.

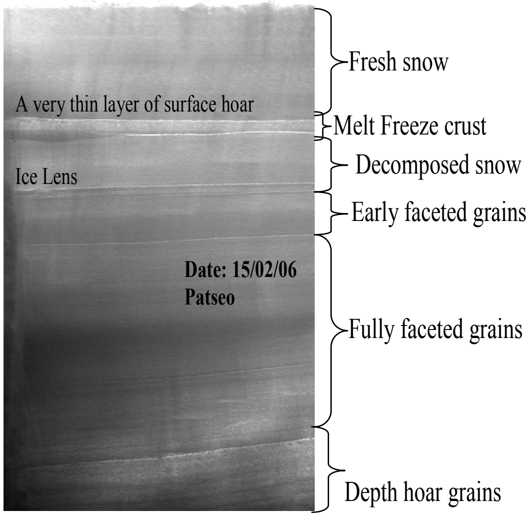


Figure. 3: A translucent profile showing various interfaces within snow pack at Patseo research station

Test Procedure

The layered snow samples made in cold laboratory under controlled conditions using above said sample preparation method were then taken for tension and shear test (to be performed at -9ºC) after sufficient sintering. Among the samples gathered after sintering, set of samples were subjected to tension under constant strain rate. Constant strain rates of $5x10^{-4}$/s, $5x10^{-5}$ /s and $5x10^{-6}$/s were applied for each experimental set simultaneously. Fifty six experiments have been done under tension with the earlier mentioned strain rates. The snow having density range of 360 Kg/m^3 to 430 Kg/m^3 used for the experiments.

Thick section micrograph of layered snow surface were shown in figure 4, which provides the clear distinction of interface at the centre.

The realistic fracture behavior at the best can be analyzed by comparing the results obtained from the layered snow sample with the homogenous snow samples. In order to establish this comparison, different sets of homogenous snow sample (with fine grain having grains size in the range of 0.5mm to 1.0mm and melt-freeze grains respectively) were prepared and allowed to age for seven days. Here we don't advocate for the size of melt-freeze grains as the melt-freeze cycle forms the cluster of grains surrounded by frozen water. Same test procedure was adopted for the homogenous samples also. After aging, these samples were also subjected to undergo tension with different sets of constant strain rates at $5x10^{-4}$/s, $5x10^{-5}$/s and $5x10^{-6}$ /s.

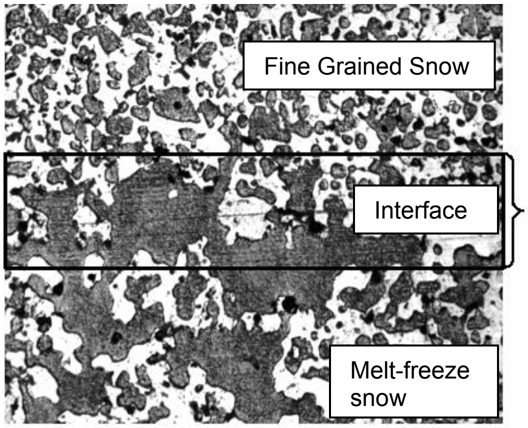


Figure. 4: Thick section micrographs of layered snow

Similar procedure was adopted to perform shear test (63 nos.) on rectangular snow samples under similar constant strain rates as mentioned earlier.

Results and Discussion

Before starting up with the actual experiments on layered snow the strength of the same was compared with homogenous rounded grain snow. Figure 5 illustrates the comparison of failure stresses under tension for layered and homogenous snow at three different strain rates ($5x10^{-4}$/s, $5x10^{-5}$/s, $5x10^{-6}$/s). From figure 5, it can be said that the failure stress for homogenous snow sample is always greater than layered snow sample for all the three strain rates. This justifies the presence of weaknesses at interface in the layered snow sample. As mentioned earlier in the test procedure, the samples were subjected to under go shear and tensile loading for three different strain rates, all the samples have failed along the interface. Percentage of samples failed from interface under tension

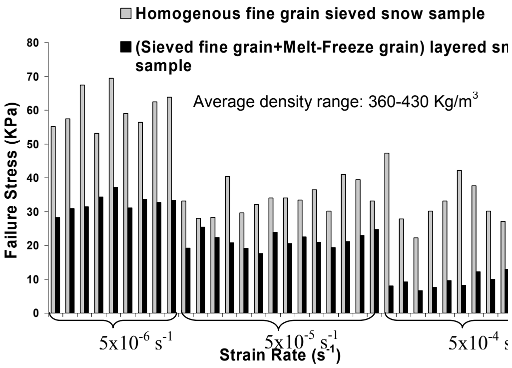


Figure. 5: Figure illustrating a comparison between the failure stresses of homogenous and layered snow.

and shear are shown in Table 1. Photographs of layered snow samples under shear and tension are shown in figure 6a and 6b. The range of failure stresses under tension and shear obtained from the experiments are tabulated in Table-2. The failure stresses under tensile and shear loading conditions for layered snow samples involving interface of fine grain sieved snow/ melt-freeze snow grains are plotted with the respective densities at which they are computed for each strain rate.

Table 1. Tensile and shear strength values of the samples at various strain rates.

Sl. No	Interface Type	Total No. of Experiments		No. of Samples Failed at Centre (Layer Interface)		No. of Samples Failed other than Centre		%age Failure from Interface	
		Strain Rates (s^{-1})	No. of Expts.	Under Shear	Under Tension	Under Shear	Under Tension	Under Shear	Under Tension
1	Melt Freeze – fine grain snow	$5x10^{-4}$	50	24	23	02	01	92.31	95.88
		$5x10^{-5}$	64	24	17	06	07	80.00	70.83
		$5x10^{-6}$	45	15	16	08	06	72.73	65.22

Table 2. Tensile and shear strength ranges for interface of rounded grain/ Melt-Freeze snow at various strain rates.

Sl. No	Interface Type	Strain Rates (s^{-1})	Range of Failure Stress (KPa)	
			Under Shear	Under Tension
1	Melt Freeze-fine grain Snow	$5x10^{-4}$	2-7	17-37
		$5x10^{-5}$	4-14	14-39
		$5x10^{-6}$	5-20	13-52

Figures 7a, 7b and 7c show such plots in which the tensile and shear strength are grouped together in the form of rectangular envelopes for these strain rates. It is quite clear from these figures that, as we move from lower strain rate (5 x 10^{-6}/s) to higher strain rate (5 x 10^{-4}/s) the distance between the two failure stresses under shear and tension gradually increases. The figures hence show the confinement of snow in a particular stress range. It implies that in lower strain rates scatter in tensile and shear strengths is very high which

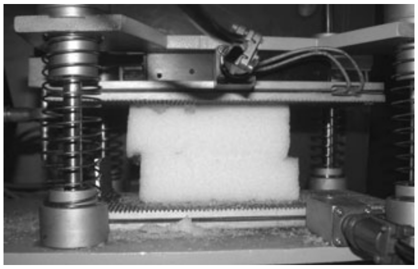


Figure. 6a: Layered sample for shear test

Figure. 6b: Layered sample for tension test

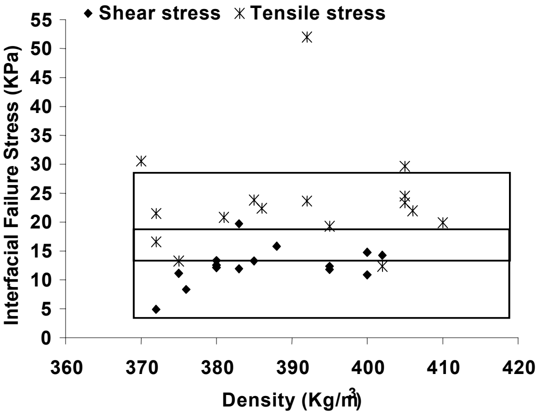


Figure. 7a. Interfacial failure stress envelopes for shear and tensile loading at a strain rate of $5x10^{-6}$/s.

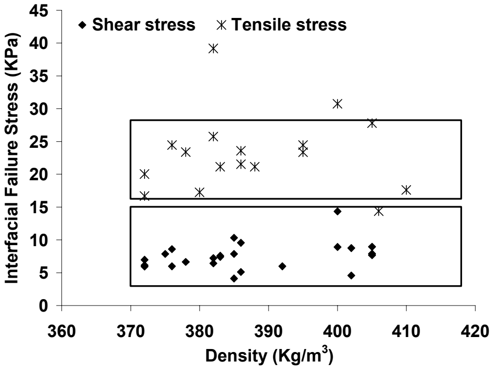


Figure. 7b. Interfacial failure stress envelopes for shear and tensile loading at a strain rate of $5x10^{-5}$/s.

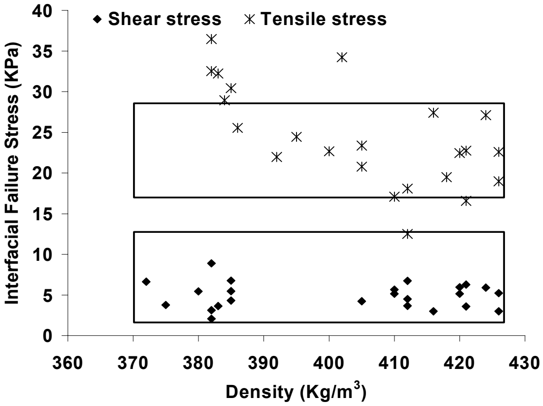


Figure. 7c. Interfacial failure stress envelopes for shear and tensile loading at a strain rate of $5x10^{-4}$/s.

in turn confirms the uncertainty of failure in lower strain rates. This uncertainty can also be seen in Table 1, which shows a lower percentage of failure of samples from interface at strain rate of $5x10^{-6}$ s^{-1}. Uncertainty of failure under tensile and shear stress decreases as we go towards higher strain rates.

Behavior of different natural snow-snow interfaces under shear loading:

The different snow interfaces react quite differently under shear loading conditions. All samples were allowed to deform either up to maximum deformation allowed by shear testing machine i.e. 20 mm or deformed up to failure. All samples were deformed at a strain rate of $5x10^{-5}$/s. Experiments were then classified on the basis of maximum deformation attained before fracture and their interface type. The layered snow samples having interface of fresh snow/felt-like snow and having deformation more than 5 mm were taken in one group while the interfaces having deformation less than 5 mm were taken in another group. The behavior of different snow-snow interfaces under shear loading is shown in Figure 8a and 8b. Figure 8a shows the load-deformation behavior of interfaces involving fresh snow/felt-like snow and deformations more than 5 mm. The curve shown with dotted lines in Figure 8a shows the load- displacement behavior of snow samples involving layers having fresh snow-early faceted snow interface. Initial lower slope of load-displacement curve involves high deformation on lower load values due to fresh snow and then

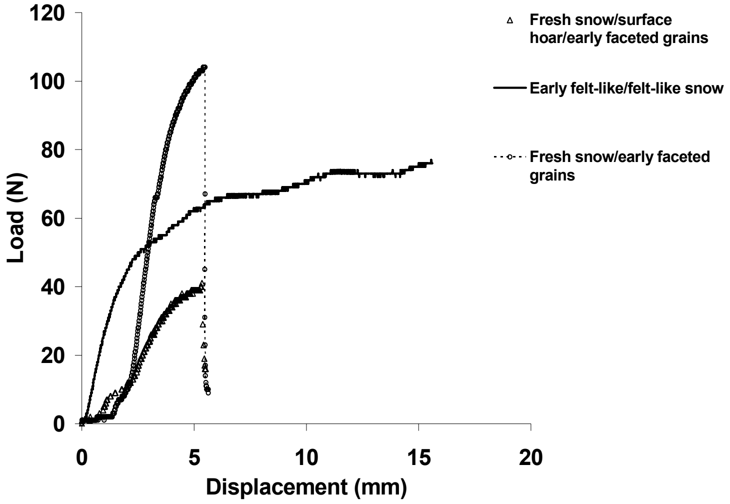


Figure. 8a. Typical load-displacement curves at a constant strain rate of 5x10^{-5} /s for natural snow samples having Interfaces involving fresh snow/felt-like snow

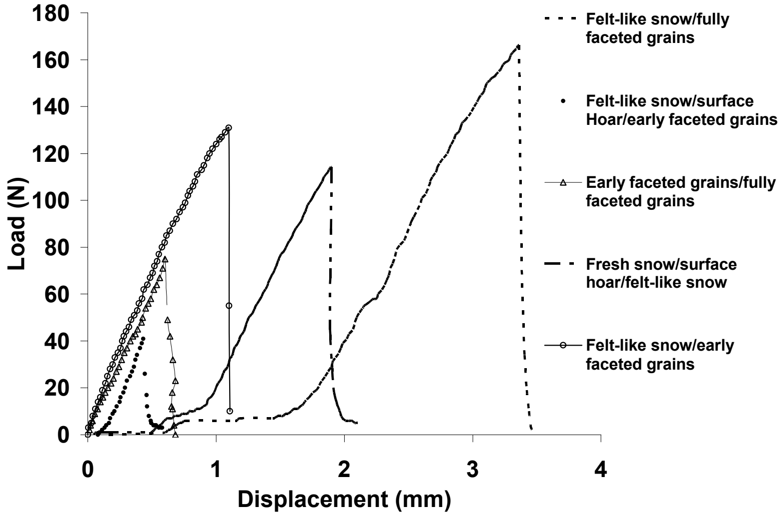


Figure. 8b. Typical Load-Displacement curves at a constant strain rate of 5x10^{-5} /s for natural snow samples having various snow-snow Interfaces

sample show steep rise in slope of the curve which involves strain hardening at the interface and the sample fails from the interface at higher load (typically 104 N here) during this process. It is to be noted here that in all the samples involving fresh snow, the layer of fresh snow is taken on the top. In the shear machine the top platens move with the help of stepper motor. Hence the load – displacement curve is initially influenced by the layer which is on the top. Once the loads are transferred from top layer snow to the interface, the curve then shows the behavior of interface only. In Figure 8a, the interface of fresh snow/ surface hoar/early faceted snow shows lowest failure load value due to involvement of surface hoar grains at the interface. Here, load-displacement curve show initial low slope similar to samples having fresh snow-early faceted snow interface. The sample then show strain hardening behavior similarly and sample fails abruptly from interface giving small deformation and low load value. The failure of these layered snow samples at lower load values may be attributed to the surface hoar present at the interface.

The curve with solid line shows a typical load-displacement behavior of the interface involving early decomposed snow (early felt-like snow) and fully decomposed snow (felt-like snow). In this experiment we had accidentally taken felt-like snow on top platen of shear machine hence initially it shows steep slope of curve due to the well settled felt-like snow and after a certain amount of deformation (typically 1-2 mm), the curve follows a gentle slope due to involvement of early felt-like snow at the interface which is characterized by low slope. The curve hence shows the influence of the snow layer sticking on the top, as in Figure 8a it reverses the behavior of load displacement curve.

Figure 8b shows the load-displacement curves of various snow-snow interfaces. From the figure, it is quite clear that the snow which involves either the surface hoar or the interface of early faceted/ fully faceted snow grains within the samples show lower values of failure load (40-125 N) and displacement (0.5 -2.0 mm). The samples having interfaces of felt-like/ early faceted snow grains give high values of failure load and relatively high values of displacement.

Conclusion

Failure stresses for various snow-snow interactions evolving interface have been evaluated from the experiments conducted under both shear and tensile loading conditions. Almost all the samples failed along the interface hence determining the interfacial failure stress. Our experiment especially on layered snow having interface of fine grained snow and melt-freeze snow observes high values of failure stresses under tensile loading than to shear loading at a particular strain rate. It is also quite interesting that, as we move from lower strain rates to higher strain rates, distinction in failure stresses of snow under tensile and shear loading conditions is quite clear. This distinction is exhibited as tensile and shear stress envelopes move apart. These transitions in failure stresses elucidate the slab avalanche release mechanism clearly. As shear strength is always lower than tensile strength, the formation of crack in shear originates first followed by tension. Before the initiation of crack within the snow pack, the weakest interface will be decided first and further the formation of super weak zone for basal shear (i.e. crack formation). This in turn activates and initiates the movement of crack further and allows it to grow gradually. The crack propagates further as stresses at the interface increases beyond a particular limit. This limit is decided by interfacial shear failure stress. Further the rate of propagation of cracks will be faster in shear in comparison to tension due to lower values of interfacial shear failure stress. While analyzing the load – displacement behavior of layered snow, we should emphasize on that portion of the curve where the slope of curve changing especially in case of fresh snow/ felt-like snow involved in the sample. The load-displacement behavior of the layered samples may be simulated using Finite element method for determination of cohesive parameters like fracture energy, critical opening distance etc. and hence to simulate the propagation of crack within a snow slab. Finite element simulation of some of these shear and tension tests were done earlier by Mahajan and Senthil (2004) and used to model the crack growth in a layered snow pack. Our results also emphasize on the importance of the interfaces of early faceted and fully faceted grains and the surface hoar buried within the snow pack as they both results in lower failure load values.

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