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Fracture energy applicable to dry snow slab avalanche release

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[1] Dry slab avalanches release by a sequence of propagating fractures: first by shear fracture (mode II and mode III) in a weak layer at the base of the slab and second by tensile fracture through the crown after which release of the slab is imminent. The fracture energy is the energy which must be provided to produce a unit area of fracture surface. It is a key parameter in determining how and when fractures will propagate and important slab characteristics such as length and width that are necessary in order to estimate slab mass and volume in relation to destructive potential. In this paper, approximate estimates of fracture energy are calculated from field measurements of slab properties, laboratory measurements and in-situ strength tests in alpine snow. Estimates of fracture energy are given for both tensile fracture (mode I) through the crown as well as for shear fracture (mode II) in fragile weak layers of slab avalanches. The results, when compared with other values from ice, rock and engineering materials, suggest that snow has the lowest values. **Citation:** McClung, D. M. (2007), Fracture energy applicable to dry snow slab avalanche release, *Geophys. Res. Lett.*, *34*, L02503, doi:10.1029/2006GL028238.

1. Introduction

[2] Dry snow slab avalanches release by propagation of fractures [*McClung*, 1979, 1981, 2003, 2005] First in the sequence is shear fracture in mode II and mode III underneath the slab within a thin weak layer or at the bottom of the slab between the slab and the weak layer. Next, tension fracture appears at the top or crown of the avalanche. The energy to create a unit area of fracture surface is the fracture energy. In order to determine the energy used as fractures propagate in mode II and mode III within the weak layer, the fracture energy G_{II} and G_{III} must be known. Similarly, the stored energy needed to drive tensile fractures vertically through the crown is fundamental and requires knowledge of the mode I fracture energy G_I. In this paper, I consider mathematical estimation of the appropriate fracture energies (G_I; G_{II}) as needed for applications in relation to dry snow slab avalanches. Along with fracture toughness [*McClung and Schweizer*, 2006], fracture energy is one of the fundamental properties that determine snow slab release. The approach in this paper is to determine values of fracture energy from field measurements related to slab avalanches.

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2. Mode I Fracture Energy for the Snow Slab

[3] The fundamental definition of fracture energy is derived from *Irwin* [1958] as:

$$K_{Ic} = \sqrt{E' G_I} \tag{1}$$

where K_{Ic}, E' are fracture toughness in tension (kPa(m)$^{1/2}$), and effective elastic modulus (kPa) respectively and G_I is the energy (N/m) to create a unit area of fracture surface in tension. The effective elastic modulus in terms of Young's modulus, E, is: $E' = E$ (plane stress) and $E' = E/(1 - \upsilon^2)$ (plane strain) where υ is the elastic Poisson ratio. For low density snow, *Mellor* [1975] suggests $\nu < 0.2$ so for plane problems, $E' \approx E$. *McClung and Schweizer* [2006] determined K_{Ic} appropriate for slab avalanche tension crown fractures through the slab from field data from approximately 300 avalanches assuming alpine snow is a quasi-brittle material with fracture mechanical size effects in tensile fracture. The simple relationship is:

$$K_{Ic} \approx 50 \left(\frac{\rho}{\rho_{ice}} \right)^{2.4} \text{ kPa(m)}^{1/2} \tag{2}$$

where ρ, ρ_{ice} are slab density and density of ice (917 kg/m^3) respectively. Equation (2) applies only for well bonded snow typical of slab material. *Sigrist* [2006] obtained a very similar relationship to equation (2) based on 3-point beam notched laboratory fracture tests: K_{Ic} = 56 $(\rho/\rho_{ice})^{2.33}$ with large scatter in the results.

2.1. Simple Estimates for Mode I Based on Volume Fraction of Ice

[4] Equation (2) represents an approximate expression for fracture toughness in tension derived from field experiments in the density range: 100–350 kg/m^3. For densities in this range, I approximate the fracture energy below in relation to the value for ice which is consistent with the assumptions to derive equation (2). As a first approximation, the fracture energy for alpine snow may be related to that for large samples of ice as:

$$G_I \approx C_0(\rho) G_{I_{ice}} \tag{3}$$

The reasoning behind equation (3) is based on the fact that dry snow is composed of ice and air. Since the air requires no energy in the fracture process, an important consideration is the fraction of a snow sample which is composed of ice. The volume fraction of a snow sample filled by ice is simply given by the ratio of the snow density to the density of ice. This suggests to a first approximation that $G_I \approx (\rho/\rho_{ice})\, G_{I_{ice}}$. From *Dempsey et al.* [1999], $G_{I_{ice}}$ = 3 N/m for large samples of fresh water lake ice. I assume lake ice has a density 917 kg/m^3. For snow densities in the range,

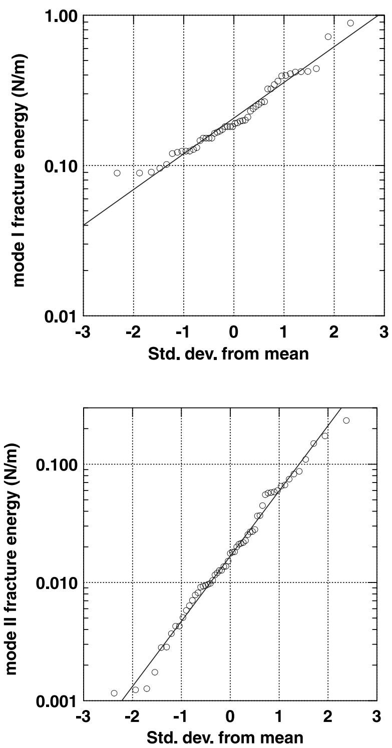

Figure 1. Probability plots of fracture energy from field data. (a) Mode I from 50 naturally triggered avalanches. The plot is made for slab density greater than 150 kg/m^3. (b) Plot similar to Figure 1a for mode II fracture energy from field data from 57 naturally triggered avalanches. The plot is made for slab thickness greater than or equal to 0.2 m. Both plots suggest that the fracture energy is log-normally distributed for the assumptions made.

100–500 kg/m^3, as expected for the range in snow slabs [*McClung and Schaerer*, 2006], the mode I fracture energy may be roughly estimated in the range: 0.3–1.6 N/m. The simple approximation above will not apply to weak layer forms such as facets which have anisotropic mechanical behaviour [*McClung and Schaerer*, 2006].

2.2. Estimates for Mode I Derived From Avalanche Fracture Line Data

[5] Another estimate may be derived from the estimates of the Young's modulus of snow. From (1), the mode I fracture energy of snow is then:

$$G_I = \frac{K_{Ic}^2}{E'} \tag{4}$$

Sigrist [2006] measured the Young's modulus with high frequency range (100 Hz) to yield an empirical relation $E' \approx E = 9.68 \times 10^5 \left(\frac{\rho}{\rho_{ice}}\right)^{2.94}$ kPa for densities in the approximate range: 200–400 kg/m^3. Application of equation (2) with this empirical relation for the effective modulus for densities greater than 150 kg/m^3 gave the following results for data from field measurements at dry slab avalanche fracture line profiles: 153 avalanches with a mix of triggers (natural, skier triggering, explosive generated): $0.09 \leq G_I$ (N/m) ≤ 0.7; mean value: 0.18 N/m.; 41 skier triggered avalanches: $0.03 \leq G_I$ (N/m) ≤ 0.4: mean value: 0.18 N/m; 50 naturally triggered avalanches: $0.09 \leq G_I$ (N/m) ≤ 0.9: mean value: 0.20 N/m. I conclude that field measurements from 244 avalanche fracture lines imply an approximate range: $0.1 \leq G_I$ (N/m) ≤ 1.0 with a mean value of $G_I \approx 0.2$ N/m. Figure 1a shows the values of G_I (N/m) calculated for 50 naturally triggered avalanches. There is considerable uncertainty about these values due to variations in estimates of $E'(\rho)$ reviewed by *Sigrist* [2006]. This is of particular concern for densities around 150 kg/m^3 for which good experimental data on Young's modulus do not exist.

[6] *Jamieson and Johnston* [1990] performed rapid, unnotched, in-situ tests and grain types appropriate for slab material. The nominal tensile strength of the experiments, f_t' (in kPa), is given by: $f_t' \approx 80\ (\rho/\rho_{ice})^{2.4}$ where ρ is mean snow density for the layer tested and ρ_{ice} is the density of ice (917 kg/m^3). *Bažant and Planas* [1998] suggest (p. 164) that the fracture energy may be estimated approximately as 1–1.67 times the product of f_t' and displacement over which the softening curve drops to zero. *McClung and Schweizer* [2006] presented a force-displacement curve for a 3-point beam tensile fracture experiment performed by Christian Sigrist. For a density of 200 kg/m^3 and displacement: 0.15 mm (from the experiment), this rule of thumb yields a fracture energy for soft, low density alpine snow of 0.3–0.5 N/m. Comparison with the estimate value for large samples of fresh water ice, 3 N/m, *Dempsey et al.* [1999] , yields an order of magnitude value for $C_0 \approx 0.1$–0.2 in equation (3). The estimated range is only from one test and using a rule of thumb but the simple analysis lends confidence to values estimated by other methods.

2.3. Comparison of Mode I Estimates With the Fracture Toughness of Single Crystals

[7] The mode I fracture energy for the stable fracture of a single crystal of freshwater ice at temperatures slightly less than 0°C is given by twice the surface energy of ice [*Rice*, 1968, p. 234] : $2\gamma_{se} = 0.218$ N/m [*Ketcham and Hobbs*, 1969; *Dempsey and Palmer*, 1999]. Taking the empirical values of E' for snow estimated above from *Sigrist* [2006], gives an empirical, hypothetical equation for fracture toughness related to single crystals. Using Irwin's relation (1) with reduction for the volume fraction filled by solids and the modulus for snow. the substitution $G_I \rightarrow 2\gamma_{se}$ [*Rice*, 1968] gives a hypothetical estimate for minimum toughness assuming the single crystal fracture energy:

$$K_{Ic(sc)} = \left[\left(\frac{0.218}{1000}\right)\left(\frac{\rho}{\rho_{ice}}\right)E'(\rho)\right]^{\frac{1}{2}} \text{ kPa(m)}^{1/2} \tag{5}$$

Comparison with equation (2) suggests $K_{Ic}/K_{Ic(sc)} \approx 2$ for densities greater than about 200 kg/m^3 and an alternate, hypothetical way to view it. Given the elastic modulus for alpine snow and its volume fraction filled by ice, its mode I fracture toughness is predicted to be about twice that for fracture of single ice crystals. For densities from 200–500 kg/m^3 the ratio is: $K_{Ic}/K_{Ic(sc)} \approx 1.8$–$2.7$. At low density, $\rho < 200$ kg/m^3, the ratio $K_{Ic}/K_{Ic(sc)} \rightarrow 1$.

[8] This is, however, purely hypothetical and it is a very simplified view. From data on large samples of freshwater

ice [*Dempsey et al.*, 1999], a comparable calculation shows that the fracture toughness of 300 kPa(m)$^{1/2}$ is about 6 times that for single crystals [*Dempsey and Palmer*, 1999]. Given the elastic modulus for snow and the volume fraction filled by ice, the estimated fracture toughness for single ice crystals may represent a lower limit for snow in tension. It might be expected that toughness could approach that for single crystals as a lower limit. This analysis suggests that fracture toughness of snow from which fracture energy is derived has a reasonable magnitude (equation (2)).

[9] The suggestion that mode I fracture energy of snow is about twice the surface energy of ice using the modulus for snow and the volume fraction is likely due physically to a combination of effects such as particle rearrangement, internal friction, plasticity and micro-cracking which are expected for a granular, quasi-brittle material [*Bažant and Planas*, 1998]. Further, snow consists of bonded single crystals and chains of bonds with different orientations to the applied stress. If they were all ideally aligned on a plane with bonds perpendicular to the maximum principal tension stress, the fracture energy might be reduced. I take the high values (relative to twice the surface energy of ice) as a signal that snow is a quasi-brittle material which implies linear elastic fracture mechanics does not apply. The fracture toughness values (equation (2)) from *McClung and Schweizer* [2006] were developed from quasi-brittle fracture mechanics using the equivalent crack concept relating true fracture toughness to apparent toughness to account for the size effect [*Bažant and Planas*, 1998, p. 110].

3. Mode II Fracture Energy for Weak Layers in Slab Avalanches

[10] The thin, fragile weak layers which are responsible for dry slab avalanche release are expected to have much lower shear fracture energy than the tensile fracture energy for the thicker, tougher slabs which sit on top of them. From *Irwin* [1958], the fundamental definition of fracture energy for mode II (G_{II}) is:

$$K_{IIc} = \sqrt{E' G_{II}} \qquad (6)$$

where K_{IIc} (kPa(m)$^{1/2}$) is the mode II shear fracture toughness for the weak layer.

3.1. Estimates from the Average Ratio K_{Ic}/K_{IIc} for Slab Avalanches

[11] *McClung and Schweizer* [2006] determined the ratio K_{Ic}/K_{IIc} for approximately 300 snow slabs. On average, the ratio is approximately 3–4 with a range between 1–18. From equations (1) and (6), the ratio of fracture energies between mode II and mode I, on average, is in the range:

$$\frac{1}{16} \leq \frac{G_{II}}{G_I} = \left(\frac{K_{IIc}}{K_{Ic}}\right)^2 \leq \frac{1}{10} \qquad (7)$$

Given the estimates for G_I above, approximate order of magnitude values for mode II fracture energy, on average, for avalanche weak layers are in the range: $G_{II} \approx 0.006$ – 0.1 N/m.

[12] In equation (7), it is assumed that the effective modulus is the same for mode I fracture through the slab and mode II fracture in the weak layer with both being the effective modulus near the slab bottom. This assumption is consistent with the size effect law derived by *Bažant et al.* [2003a] for mode II fracture within the weak layer and the assumptions by *McClung and Schweizer* [2006] in deriving the ratio K_{Ic}/K_{IIc}.

3.2. Direct Calculations of G_{II} Using the Modulus and Slab Avalanche Properties

[13] Direct calculations are presented here using the empirical modulus $E'(\rho) = 9.68 \times 10^5 \ (\rho/\rho_{ice})^{2.94}$ kPa obtained by *Sigrist* [2006] and the expression for K_{IIc} obtained by *McClung and Schweizer* [2006]. The calculations were made for slab depths in the range: 0.2–2 m. This gave the following results for data from 278 avalanche fracture lines: 176 avalanches with a mix of triggers: $0.001 \leq G_{II}$ (N/m) ≤ 0.2; mean: 0.016 N/m; 45 skier triggered avalanches: $0.001 \leq G_{II}$ (N/m) ≤ 0.2; mean: 0.0010 N/m; 57 naturally triggered avalanches: $0.001 \leq G_{II}$ (N/m) ≤ 0.2; mean: 0.017. I conclude from the avalanche fracture line data: $0.001 \leq G_{II}$ (N/m) ≤ 0.2 with a mean value: $G_{II} \approx 0.015$. Figure 1b shows the values of G_{II} (N/m) calculated data for 57 naturally triggered avalanches.

[14] These values estimated above from field data on slab avalanches compare favourably with the in-situ estimates of G_{II} for a weak layer of faceted crystals and depth hoar 1–3 mm in size reported by *Sigrist* [2006]. His 33 values are in the range: $G_{II} \approx 0.04 - 0.09$ (N/m). *Sigrist* [2006] and *Sigrist et al.* [2006] also reported on layered cantilever beam tests (27 tests) with the same range of results: $G_{II} \approx 0.04 - 0.09$ (N/m).

4. Fracture Energy in Shear for Homogeneous Snow from Lab Tests in Simple Shear

[15] *McClung and Schweizer* [1999] reported data from direct simple shear strain-softening tests on homogeneous alpine snow (not snow for fragile weak avalanche layers). By application of the cohesive crack model [*Palmer and Rice*, 1973], the fracture energy may be estimated as about 40% of the area under the strain-softening curve [*Bažant and Planas*, 1998; *Bažant et al.*, 2003b; *McClung and Schweizer*, 2006]. From *Palmer and Rice* [1973], the fracture energy may be estimated from the tests including the 40% reduction in area as:

$$G_{II} = 0.4\left(\frac{32}{9\pi}\right)\omega \qquad (8)$$

From *McClung and Schweizer* [1999] values for the end zone size ω (fracture process zone), calculated for all of the area under the softening curve, are in the range: 1.5–3 m. With these values, G_{II} is in the range: 0.7–1.4 N/m. The lowest value is approximately a factor of 3 higher than the extreme upper limit for G_{II} estimated above for fragile weak layers in avalanches.

[16] The values of G_{II} for homogeneous snow may be compared with those estimated in tension above for densities in excess of 150 kg/m^3: $G_I \approx 0.1$–1. I conclude that for homogeneous snow, not of the fragile types found in weak layers, the fracture energy in shear is comparable to that in

Table 1. Estimates of Fracture Energy for Alpine Snow

Type	Range, N/m	Source	Comments
G_I	0.09–0.9	244 slab avalanches [*McClung and Schweizer*, 2006]	Values estimated for slab material from dry slab avalanches
G_{II}	0.001–0.2	278 slab avalanches [*McClung and Schweizer*, 2006]	Values estimated for fragile weak layers from dry slab avalanches
G_{II}	0.04–0.09	1 weak layer of facets and depth hoar [*Sigrist*, 2006]	In-situ estimates for one fragile weak layer (33 measurements)
G_{II}	0.04–0.09	Estimates for facets, mixed forms and depth hoar in weak layers [*Sigrist*, 2006; *Sigrist et al.*, 2006]	Laboratory measurements from cantilever beam tests with weak layers (27 measurements)
G_{II}	0.7–1.4	Lab simple shear tests [*McClung and Schweizer*, 1999]	Estimates for homogenous snow comparable to slab material for more than 100 simple shear tests

tension but perhaps somewhat higher. This suggestion that values in shear exceed those in tension is expected since normally the shear strength of homogeneous material exceeds tensile strength. *Selby* [1993] presents data (p. 81) from different types of rock which show the shear fracture strength is about twice the tensile strength. Table 1 contains a summary of the estimates of G_I, G_{II} and all the sources of the estimates.

[17] Observations e.g., *Perla* [1971] show that on the flanks of fallen avalanches, the fracture pattern is sometimes a sawtooth pattern which suggests tensile fracture and sometimes straight which suggests shear fracture. The estimates in homogenous snow suggest that G_I and G_{II} are of comparable magnitude and they may help to explain the observations of flank fracture patterns. With comparable values, one might expect either flank fracture pattern (sawtooth tension or straight shear) to be observed depending on snow type and force application. Both the estimates of fracture energy in homogeneous snow are much larger than for fragile weak layers of avalanches. This serves to explain why emphasis in avalanche release mechanics is focused on initial mode II fracture in the weak layer rather than tensile mode I failure in the slab. Energetically, mode II shear fracture in the weak layer is much more favorable. This is opposite to isotropic engineering materials where emphasis is on mode I fracture. Since G_I and G_{II} for the slab material were determined here by independent methods and since flank fractures can appear in either tension or shear in avalanche fractures, confidence is increased that the values of are of similar magnitude as suggested by the analysis.

5. Summary and Discussion

[18] The fracture energy of alpine snow in mode I (for the slab body) and mode II (representing the fragile weak layers) is of fundamental importance in snow slab avalanche release. From the analysis, alpine snow as found in snow slabs has the approximate mean value for mode I, $G_I \approx 0.2$ N/m). This may be compared with other common materials: lake ice (3 N/m) from *Dempsey et al.* [1999]; rock (10 N/m) from *Friedman et al.* [1972] and *Brace and Walsh* [1962]; concrete mortar (20 N/m) and concrete (30–45 N/m) from *Bažant and Planas* [1998]; and steel ($70-200 \times 10^3$ N/m) from *Broek* [1986]. Based on strength and other considerations, alpine snow is expected to be the weakest of the natural materials (snow, ice, soil, rock) [*McClung and Schaerer*, 2006] so the study here may suggest a lower limit for the natural earth materials.

[19] The range for G_{II} in this paper is derived by two methods. First by estimating the ratio of fracture toughness in mode I (for the slab) to mode II (for the weak layer) for 299 slab avalanches from field data [*McClung and Schweizer*, 2006] taking into account fracture mechanical size effects for both the slab and weak layer. *McClung and Schweizer* [2006] also showed that the estimated ratio K_{Ic}/K_{IIc} is very close to the ratio of nominal tensile strength estimated from in-situ measurements by *Jamieson and Johnston* [1990] and estimates of nominal shear strength estimated from avalanche fracture line data. The second method for estimating G_{II} is by direct calculations using field measured slab properties and the modulus for alpine snow.

[20] The proposed range of values for shear fracture of fragile weak layers for slab avalanches is : $G_{II} = 0.001-0.2$ which is extremely low in comparison to any of the mode I values above. The values for G_{II} are supported by the studies of *Sigrist* [2006] and *Sigrist et al.* [2006] who determined the fracture energy for a single weak layer based on analysis and in-situ measurements, and from cantilever beam laboratory measurements. More such estimates are needed to strengthen the conclusion and determine the range more accurately.

[21] Taking mean values for $G_{II} = 0.015$ N/m and $G_I = 0.2$ N/m suggests that, on average, the fracture energy for mode I through the body of the slab is more than 10 times the energy to drive shear fractures through the weak layer. This provides the basis for avalanche prediction. The shear fracture propagates first and being the weakest entity, it is given primary emphasis in field measurements. For isotropic materials, emphasis is on mode I but for the orthotropic snow slab/weak layer configuration this would not suffice. Since slab avalanches release by propagating fractures, emphasis must be placed on fracture energy or fracture toughness to predict instability rather than snow strength. Snow strength by itself has no meaning and is inadequate to describe fracture initiation of the snow slab [*Bažant et al.*, 2003a].

[22] The fracture energy values in this paper are largely based on field measurements from fracture lines of fallen avalanches combined with in-situ strength tests and basic laboratory tests as described by *McClung and Schweizer* [2006]. Thus, it cannot be expected that the results are highly precise. The advantage of field measurements is that a wide range of conditions is represented.

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