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Dry snow slab shear fracture speeds

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[1] Dry snow slab avalanches release by propagating shear fractures within thin weak layers underneath thicker, stronger planar slabs. In this paper, measured shear fracture speeds from small scale snow slabs are compared with theoretical estimates compatible with dynamic fracture mechanics. Given the important physical quantities including density and elastic shear modulus, it is concluded that estimated snow slab shear fracture speeds scale with the shear wave speed similar to estimates in other geophysical applications including shear fractures from earthquakes and in engineering materials. However, the constant of proportionality is much lower than for alpine snow than for earthquakes and engineering materials. The lower constant of proportionality may indicate the possibility of important energy dissipation mechanisms in snow avalanche fracture propagation. **Citation:** McClung, D. M. (2007), Dry snow slab shear fracture speeds, *Geophys. Res. Lett.*, *34*, L10502, doi:10.1029/2007GL029261.

1. Introduction

[2] Snow slab avalanches release by rapid propagation of a shear fracture in a weak layer underneath a snow slab or at the interface between the slab and the weak layer [*McClung*, 1979, 1981, 2003, 2005a, 2005b]. Sometimes the weak layer is of finite thickness (one to several cm) and it is observed that collapse (vertical deformation) takes place within the weak layer (a few mm). In a previous paper, I adopted [*McClung*, 2005b] a theoretical framework from dynamic fracture mechanics based on proportionality between terminal shear fracture propagation speed and the shear wave speed in the snow slab. I compared the estimated speed with a single measurement on horizontal terrain reported by *Johnson et al.* [2004]. In this paper, I compare the theory with new speed data reported by *van Herwijnen and Jamieson* [2005] from small slabs on steep slopes triggered by skiers and the result of *Johnson et al.* [2004]. In addition, new estimates of the elastic shear modulus are available [*Sigrist et al.*, 2006]. Since more than one speed estimate is available here, it becomes possible for the first time to examine how the speeds scale with the shear wave speed.

[3] All the snow slab measurements analysed in this paper are from fracture of thin weak layers underneath snow slabs. The weak layers are one to several cm thick with measurable vertical displacement so that some collapse is present during the fracture propagation for all the test results. The speed measurements are consistent with the suggestion of *McClung* [2005b] that shear fracture speed scales with the shear wave speed but the conclusions are substantially changed. On comparison with earthquake shear fracture speeds, it is suggested that, given the shear wave speed for the material, $C_S = \sqrt{\mu/\rho}$, where ρ, μ are slab density and elastic shear modulus, the measured fracture speeds scale as proportional to the shear wave speed for both earthquakes and snow avalanches. However, the constant of proportionality for snow slabs at about 0.1is much lower than for earthquakes (0.7 – 0.9).

2. Empirical Estimate of Terminal Snow Slab Shear Fracture Speeds

[4] The speed of a propagating shear disturbance depends on the rate at which energy is fed to the tip of the disturbance. *Johnson et al.* [2004] provided a speed measurement of about 20 m/s for a propagating disturbance under a snow slab on horizontal terrain using seismic techniques and *van Herwijnen and Jamieson* [2005] have given more data from steep slopes. The data of *van Herwijnen and Jamieson* [2005] are from small snow slabs similar to avalanches triggered by a skier. The speed estimates are from high speed photography. From dynamic fracture mechanics [*Freund*, 1990; *Fossum and Freund*, 1975; *Heaton*, 1990] and experimental evidence from engineering materials and earthquake fractures, I suggested [*McClung*, 2005b] that the terminal speed for avalanche fractures could be slightly less than the approximate range: $V_t = (0.7 - 0.9)\sqrt{\mu/\rho}$for earthquake fractures. This estimate from *McClung* [2005b] was made from only one speed measurement by *Johnson et al.* [2004] so that scaling of speeds could not be attempted. Below, I show that the available estimates of avalanche speed by both *Johnson et al.* [2004] and *van Herwijnen and Jamieson* [2005] combined with new estimates of μ by *Sigrist et al.* [2006] are closely matched by a much lower estimate with an average proportionality factor of 0.12:

$$V_t = 0.12\sqrt{\frac{\mu}{\rho}} \quad (1)$$

3. Estimates of the Effective Shear Modulus for Viscoelastic and Elastic Cases

[5] Alpine snow is a viscoelastic material [*Bader and Kuroiwa*, 1962]. For a linear viscoelastic material, the plane shear wave speed is given by [*Fung*, 1965]:

$$C_S = \left\{ \mathrm{Re}\left[\sqrt{\frac{\rho}{\mu(\omega)}} \right] \right\}^{-1} \quad (2)$$

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Table 1. Comparison of Speed Estimates From Equation (1) and Equation (5)[a]

Weak Layer Crystals	ρ, kg/m^3	ψ, deg	Equation (1)[b]	Equation (5)[c]	Measured Speed, m/s
test 1: Surface hoar	190	0	22	23	20 ± 2
test 2: Surface hoar	175	32	22	20	21 ± 6
test 3: Surface hoar	132	44	20	15	21 ± 8
test 4: Depth hoar	199	33	23	24	23 ± 6

[a]With measured shear fracture speeds from small skier triggered avalanches (tests 2, 3, 4, from *van Herwijnen and Jamieson* [2005]) and an estimate from a propagating disturbance on flat terrain (test 1, from *Johnson et al.* [2004]). The value of $\mu_S(\omega)$ is estimated by extrapolation of the data of *Camponovo and Schweizer* [2001] using equation (4) and the value of μ is estimated assuming ν = 0.2 to derive equation (6).
[b]V_t(m/s); ω = 100 Hz.
[c]V_t(m/s); ω = 1 Hz.

where $\overline{\mu(\omega)}$ is the complex shear modulus as a function of frequency for a given temperature and density. The shear modulus for snow may also depend slightly on structure or texture but such effects are unknown and not considered here. If the material is linear elastic, $\overline{\mu(\omega)}$ becomes a real number, independent of ω and the shear wave speed becomes independent of frequency. From equation (2), the shear wave speed may be expressed as a function of the real part of the shear modulus, also called the storage modulus [*Mellor*, 1975; *Camponovo and Schweizer*, 2001], $\mu_S(\omega)$ = Re[$\overline{\mu(\omega)}$]. Equation (2) is then replaced by:

$$C_S = \sqrt{\frac{\mu_S(\omega)}{\rho}} \tag{3}$$

In the elastic limit, the elastic shear modulus at high frequency, μ, replaces the storage modulus $\mu_S(\omega) \rightarrow \mu$ = *const*. and the modulus becomes a real number independent of frequency.

[6] Estimates of the storage shear modulus are available from *Camponovo and Schweizer* [2001] at a frequency ω = 1 Hz. They measured $\mu_S(\omega)$ directly in the range 0.38–0.8 × 10^3 kPa for alpine snow with densities in the range: 215–255 kg/m^3 at temperature of −4°C. The snow they used had hand hardness index 2 also called soft snow (see *McClung and Schaerer* [2006] for the hardness scale). Their use of soft alpine snow is important since it closely matches the snow conditions under which the fracture speed measurements have been made.

[7] The regression line through the data provided by *Camponovo and Schweizer* [2001] gives a relation between the storage shear modulus $\mu_S(\omega)$ (*Pa*) and snow density ρ (kg/m^3):

$$\log_{10}[\mu_S(\omega)] = 5.58 + 0.00857(\rho - 215); \mu_S(Pa), \omega = 1\,Hz \tag{4}$$

[8] Below in Table 1, I show that speeds from small snow slabs are matched by the empirical expression with an average proportionality factor 0.65:

$$V_t = 0.65\sqrt{\frac{\mu_S(\omega)}{\rho}} \qquad \omega = 1\,Hz \tag{5}$$

if equation (4) is used to estimate the shear storage modulus.

[9] From high frequency measurements, *Sigrist et al.* [2006] provided estimates of the Young's modulus E at a frequency ω = 100 Hz where $\mu = E/[2(1+\nu)]$. According to *Mellor* [1975] this frequency (100 Hz) may not even be high enough to be completely in the elastic range. Mellor provides data from flexural vibration at high frequencies which, when compared with the values of *Sigrist et al.* [2006] at density 400 kg/m^3, suggest that the flexural values provided by Mellor are at least 50% higher. However, differences in snow hardness and aging may have an effect. At a frequency of 200 Hz, *Mellor* [1975] presents data which show the tangent of the loss factor as 0.05. Thus, the 100 Hz results of *Sigrist et al.* [2006] may still provide values for the elastic Young's modulus which are slightly below the true elastic values.

[10] For densities in the range: $200 \le \rho$ (kg/m^3) ≤ 400, I assume Poisson's ratio ν = 0.2, and I took values of Young's modulus from *Sigrist et al.* [2006] to give approximate estimates for the elastic shear modulus:

$$\log_{10}(\mu) = 6.05 + 0.004\rho; \mu(Pa); \omega = 100\,Hz \tag{6}$$

[11] It is of interest that for ρ = 200 kg/m^3, the elastic value from equation (6) is a factor of 25 higher than the viscoelastic, low frequency value from equation (4). These results suggest that alpine snow is much more prone to viscous effects than ice. For polycrystalline ice in the frequency range 1–100 Hz, at −10°C, data presented by *Sinha* [1978] suggest that the effective modulus (the quotient of applied stress and strain) increases by about 10%.

[12] *Mellor* [1975] gave estimates of Young's modulus, E, based on the data on static creep tests of *Kojima* [1954] from which $\mu = E/[2(1+\nu)]$ can be estimated. The values reported by *Mellor* [1975] are between those of equation (4) (1 Hz) and equation (6) (100 Hz). It is virtually certain that the estimates reported by Mellor contain viscous effects and do not represent either the true Young's modulus or the elastic shear modulus. *Mellor* [1975] suggests that the values from the static creep tests may be too low by a factor of 5. Since equations (4) and (6) represent low frequency and high frequency estimates respectively they are used below to calculate lower and upper bounds on the effective shear modulus.

[13] Of the earth materials (soil, earth, rock, snow), alpine snow is by far the weakest. In fact, alpine snow is probably the least likely of the earth materials to display pure elastic deformation. The low volume fraction filled by solids

(typically 20% for avalanche applications) and a presence of temperatures in alpine snow packs above 90% of the homologous melt temperature can combine to produce viscous effects unless deformation is very rapid. For snow (or ice), a clear distinction has to be made between the elastic modulus (e.g. equation (6)) which can be measured only at high frequencies and the effective modulus (e.g. equation (4)) at lower frequencies or from static creep tests. The effective modulus [*Sinha*, 1978; *Mellor*, 1975] represents a combination of truly elastic (recoverable) and mixed viscoelastic response that depends on load, time and temperature for a given density and frequency. On the other hand, the elastic modulus depends primarily on density and is independent of frequency and nearly independent of temperature [*Mellor*, 1975].

4. Estimates of Terminal Snow Slab Speed Based on Limits of the Effective Shear Modulus

[14] Table 1 shows comparison of speed estimates from equations (1) and (5) compared with the field measurements of *Johnson et al.* [2004] and *van Herwijnen and Jamieson* [2005] from small skier triggered snow slabs (ψ is slope angle). The data from the small snow slabs were obtained by excavating a 4 m long trench along side the slope so that markers could be placed just above the weak layer to estimate the propagation speed. They also reported other measurements from smaller scale instability tests including rutschblock and compression tests. However, these latter test data are not analyzed here since they are very small in scale and are probably too small to be applicable to avalanches. See *McClung and Schaerer* [2006] for a discussion of rutschblock and compression tests. *van Herwijnen and Jamieson* [2005] suggest that the best estimates of propagation speed in their data come from slope-normal displacements of their markers since, in most tests, the slab above the weak layer moved down-slope after the weak layer had fractured. Therefore, the estimates below for measured speeds are taken from slope-normal displacements as the shear fracture passed. Note that the speed estimates are slope parallel estimates from displacements of slope-normal markers. The value of density 132 kg/m^3 (test 3) may be too low to extrapolate the storage shear modulus safely using equation (4) since it lies considerably outside the densities measured (215–255 kg/m^3) by *Camponovo and Schweizer* [2001]. However, the speed comparison for test 3 still indicates a value (15 m/s) within the measurement error (21 ± 8 m/s). I assume that the speeds reached terminal values in their initial growth phase as suggested by *Mindess et al.* [1986] for data on concrete and the theoretical analysis supplied by *Freund* [1990].

[15] The comparisons in Table 1 show that the available data scale as $V_t = \sqrt{\mu_S(\omega)/\rho}$ with $V_t = 0.65\sqrt{\mu_S(\omega)/\rho}$; ω = 1 Hz (equation (5)) and $V_t = 0.12\sqrt{\mu/\rho}$; ω = 100 Hz (equation (1)). The coefficients (0.65 and 0.12) were determined by least squares fits to the values of the shear wave speed for each frequency.

[16] There are no accompanying slab or weak layer strain-rate measurements with the speed data. With a propagation speed of 20 m/s and weak layer thickness of on the order of 0.02 m, an approximate estimate of shear strain-rate within the weak layer would be $\dot{\gamma} \approx$ [20 m/s / 0.02 m] = 1000/s. The strain-rate estimate is five orders of magnitude above that required to initiate brittle fracture in snow of 10^{-2}/s in alpine snow as suggested by *Mellor* [1968]. Based on this estimate, I expect that slab strain-rates at the base of the slab would approach or exceed that needed for elastic deformation. *van Herwijnen and Jamieson* [2005] also suggested that elastic deformation is appropriate for their experiments. Thus, I suggest that the most appropriate expression for the present study is the elastic estimate: $V_t = 0.12\sqrt{\mu/\rho}$; ω = 100 Hz. However, since slab deformation strain-rates are not available some viscous dissipation cannot be completely ruled out.

5. Comparison With a Flexural Wave Model

[17] *Heierli* [2005] modelled the result of *Johnson et al.* [2004] (test 1 in Table 1) as a thin elastic beam with a flexural wave propagating on horizontal terrain (slope angle ψ = 0°). Heierli's model does not include horizontal (or longitudinal) deformation so it is only applicable on horizontal terrain (ψ = 0°). Below, I compare the estimated wave speed with the speed estimate for test 1 in Table 1.

[18] *Heierli* [2005] estimated the wave speed as:

$$c = \left(\frac{gE'D^2}{24(\Delta y)\rho}\right)^{1/4} \tag{7}$$

where $E' = E/(1 - \upsilon^2)$ (plane strain) and $E' = E$ (plane stress). In equation (7), D is slab thickness (0.40 m), g is magnitude of acceleration due to gravity, and Δy is estimated vertical collapse of the weak layer: 0.002 m. Use of the high frequency data (100 Hz) of *Sigrist et al.* [2006] from equation (6) for approximating the Young's modulus E with ν = 0.2 gives c = 40 m/s which is double the measured estimate of *Johnson et al.* [2004]. The flexural wave model is entirely elastic and it is beyond the scope here to compare with the viscoelastic case appropriate for lower frequency such as equation (4). According to *Fung* [1965], the correspondence principle for obtaining a viscoelastic solution from an elastic one by substituting the viscoelastic modulus for an elastic one will hold if the boundary conditions for both are identical. However, the boundary conditions for the viscoelastic case have not been presented for this model and it would be required to show that the strain-rates are low enough to justify the use of a viscoelastic modulus for this example.

6. Comparison With Mode I Data From Engineering Materials, Concrete, and Snow

[19] Speeds of tensile (mode I) fractures in small laboratory samples have been estimated for snow to be around 20 m/s [*Sigrist*, 2006] for similar snow densities as considered in this paper. The speed of mode I fractures scaled with elastic shear wave speed is given for engineering materials by *Kanninen and Popelar* [1985] as typically in the range: 0.4–0.6 C_S.

[20] Concrete is a quasi-brittle material with fracture character somewhat similar to snow [*Bažant et al.*, 2003; *McClung*, 2005a; *McClung and Schaerer*, 2006]. For both materials, a finite fracture process zone comparable to characteristic sample dimensions is expected. For concrete,

the estimates of mode I fracture speed are on the order of about 0.27 C_S [*Bindiganavile and Banthia*, 2005]. *Mindess et al.* [1986] reported mode I speeds in hardened cement paste, steel fibre reinforced concrete and conventional reinforced concrete as about 0.05 C_S. However, according to N. Banthia (personal communication, 2006) these latter values are not considered as accurate as those of *Bindiganavile and Banthia* [2005] since they are based on the extension of the visual crack tip effective crack length rather than the effective crack length. The multiplier on C_S (0.27) from the values of *Bindiganavile and Banthia* [2005] is still greater than the elastic values estimated here of 0.12 C_S for mode II snow slab fracture and the mode I results of *Sigrist* [2006]. The estimates from both the quasi-brittle materials snow and concrete can be expected to have reduced energy supply to the failing region which might limit speeds. However, the concrete data are from mode I and the snow slab data are from mode II. The materials differ considerably since volume fraction filled by solids is about 20% for snow and up to 85% for concrete. Also, the snow slab speeds are for weak layers which can involve collapse to consume energy.

7. Summary

[21] The available data from small scale slab shear fractures suggest that terminal speeds scale as proportional to the shear wave speed. Since snow is a viscoelastic material, the effective shear modulus can depend on rate of load application for snow of a given density. From Table 1, the estimates for terminal speed are in the range: $0.12\ C_S \leq V_t \leq 0.65\ C_S$ where the multiplier 0.12 applies to the high frequency (elastic) limit (100 Hz) and 0.65 applies for a frequency of 1 Hz (viscoelastic deformation). For comparison, mode II shear fracture speeds for earthquakes [*Fossum and Freund*, 1975; *Freund*, 1990; *Heaton*, 1990] are in the range: (0.7–0.9) C_S. For propagating fractures at speeds of 20 m/s, as in the case for the small snow slabs used here, the usual assumption [e.g., *van Herwijnen and Jamieson*, 2005] is that the deformation is fast enough to be in the elastic range which is in support of the expression $V_t = 0.12\ C_S$. Even if the low frequency value for effective shear modulus is chosen, the multiplier on C_S is below the lower limit for earthquakes.

[22] There are several possible reasons for a reduced multiplier on C_S in comparison with the equation from earthquake shear fracture speeds. First, the average rate that energy is fed into the tip (failure process zone) can be lower when slope normal deformation (i.e. collapse of several mm) is involved as in the failure of thick layers of persistent forms to which the data in Table 1 apply. As discussed above, alpine snow is quasi-brittle so that the combination of shear and collapse deformation in the fracture process zone would be expected over the finite sized region of the fracture process zone (FPZ). For the snow slabs on slopes, loss of gravitational potential energy drives shear fractures forward. The energy delivered might be more efficient if it is used exclusively to drive shear deformation in the weak layer rather than being shared by vertical deformation (including bending) and shear deformation. The snow slab speed measurements all had measurable vertical displacement (collapse of several mm) associated with them. Thus, it is possible that other avalanche failures for which weak layer thickness is only about 1 mm or less, with collapse largely absent, could have a slightly higher multiplier on C_S in comparison to those with collapse. Such a dissipation mechanism (both shear and collapse in a finite size FPZ) could be thought of as related to higher fracture energy. This mechanism would be essentially time independent. If the fracture energy is higher, then the most important effect is that greater load is required for propagation to begin and it would not be expected that the fracture speed is affected much if at all.

[23] A second, and perhaps more likely explanation, is that time dependent mechanisms affect the speeds. In general, the snow in avalanche weak layers and the slab material typically has only about 20% volume fraction filled by solids or 80% air [*McClung*, 2005b]. The experimental values quoted in this paper all have slabs with volume fraction filled by solids (ice) of about 20% or less. Thus, the slab material is time dependent (viscoelastic) and the time dependence of the material may affect the speeds in a manner fundamentally different than for engineering materials or for earthquake fractures. Time dependent dissipation could alter the speeds in two related ways: (1) damping due to viscoelastic behaviour of snow and (2) damping due to fracture induced flow of air through the pores in the snow. The combination of these two time dependent factors, as expected in avalanche fractures, might produce speeds with a scale factor below those estimated for earthquake fractures.

[24] Considering the uncertainties involved in estimating the speeds in the field and the shear wave speed, C_S, the precise scaling agreement of the speeds in Table 1 with equations (1) and (5) has to be considered somewhat fortuitous since the data are all from small avalanches with very limited slab density variations. I expect that when more data become available the multiplier on C_S will assume a range of values as with earthquake fractures. Snow densities involved in slab release range from about 100–500 kg/m^3 [*McClung and Schaerer*, 2006] with weak layer thicknesses from less than 1 mm to 10 cm. The snow densities in the present study range only from 132–199 kg/m^3. The combination of density variations, different weak layer forms and variations in weak layer thickness and combinations of snow pack stratigraphy (hardness variations in layers) should produce a range of scaled shear fracture speeds for snow slab avalanches. The limited amount of data relevant to the elastic modulus of snow presented by *Sigrist et al.* [2006] may also be a factor. When more data become available, the empirical relation in equation (6) may need to be altered which could change the scaling or the multiplier on C_S.

[25] The additional new data on the Young's modulus for alpine snow from *Sigrist et al.* [2006] and the additional information on avalanche speeds from *van Herwijnen and Jamieson* [2005], force important changes that are implicit for modelling fracture dynamics in avalanches. The multiplier on C_S of about 0.5–0.6 that I obtained in my previous paper implies that it is essential to account for inertial effects in modelling fracture dynamics [*Freund*, 1990]. However, the elastic modelling in this paper impies a multiplier of 0.12 which suggests an inertial effect which is not highly significant for estimating the dynamic stress

intensity factor. For a multiplier of about 0.1 on shear wave speed, *Freund* [1990, p. 333] shows that the mode II dynamic stress intensity factor is reduced by a few percent from the static value by inertial effects whereas for a multiplier of 0.65, the reduction is about 30%, which is very significant.

[26] The other important result from this paper is that fracture speeds from four examples are available to show that the fracture speeds scale with C_S as I previously suggested based on only one measurement [*McClung*, 2005b].

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