Towards a field test for fracture propagation propensity in weak snowpack layers

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ABSTRACT. Slab avalanche release requires fracture initiation and propagation in a weak snowpack layer. While field tests of weak-layer strength are useful for fracture initiation, the challenge remains to find a verified field test for fracture propagation. We introduce the two current versions of a field test for fracture propagation propensity, and report results of testing conducted in the Columbia Mountains of British Columbia, Canada, during the winter of 2005. By extending the column of a stability test approximately 3 m in the downslope direction, the test method allows for the development of a flexural wave in the slab, and thereby maintains the contribution of this wave and the associated weak-layer collapse to the fracture process. Fracture lengths collected on a day and location where the propagation propensity of the snowpack was locally high show a bimodal distribution, with approximately 50% of observed fractures similar to those collected in stable snowpacks, and approximately 50% with much longer fracture lengths.

INTRODUCTION

Slab avalanches are a consistent threat to winter back-country travelers as well as transportation and utility corridors in the mountainous regions of western Canada, Europe and Asia. The release of snow slab avalanches is the result of failures and fractures within a mountain snowpack. The fracture that occurs in a weak layer of snow below a stronger 'slab' is the first and most important in the sequence of fractures that lead to an avalanche (e.g. McClung, 1987). These weak-layer fractures must first initiate and then propagate, and the snowpack and stress conditions for these two stages of fracture are sometimes very different, especially for triggering by localized dynamic surface loading such as a skier or explosive (e.g. Schweizer, 1999; Schweizer and others, 2003). The strength of the weak layer has been successfully applied in strength–stress ratios which correlate with human triggering on nearby slopes (Föhn, 1987b; Jamieson and Johnston, 1998), and several common field methods that assess weak-layer strength or stability are available (e.g. Roch, 1966; Perla and Beck, 1983; Föhn, 1987a; Jamieson, 1999). However, accurate prediction of the likelihood of an avalanche occurring requires knowledge, not only of the strength of a weak layer, but also the propensity of the snowpack to propagate fractures to an extent that leads to slab avalanching.

Until recently, the propagation of brittle fractures within a layered snowpack has only been examined theoretically. McClung (1979, 1981) proposed a slab release model based on the principles of fracture mechanics and the initially ductile fracture processes that lead to self-propagation of the tip of an existing flaw. For brittle fracture, the Griffith criterion (Broek, 1982) states that a fracture will propagate where the elastic energy in the material adjacent to a crack or flaw exceeds the energy required to create new fracture surfaces (surface energy of the material). Another approach, which leads to analogous results, relates the far-field stress at fracture, σ_c, to the material parameter K_c, which is the critical stress intensity factor, or fracture toughness, for the material. The critical length, α_c, is the length of fracture at which the energy or stress criteria are met for a given load and material. McClung (1979, 1981) included the mode II fracture toughness, K_{IIc}, in his model for snow slab release, which Bažant and others (2003) refined. Kirchner and others (2000, 2002a, b), Failletez and others (2002) and Schweizer and others (2004) attempted to measure the fracture toughness of snow in the laboratory or in situ. All found snow to have extremely low fracture toughness; however, toughness measurements and applications to natural layered snowpacks proved difficult. Sigrist and others (2005) confirmed a specimen size and shape effect in measurements of fracture toughness in snow.

While observing propagating fractures in the field, Schweizer and others (1995), Johnson and others (2004) and Van Herwijnen (2005) reported slope-normal displacement of the slab as fracture occurred in the weak layer. They observed this displacement occurring progressively across an isolated column of snow. In addition, Johnson (2001) and Johnson and others (2004) argued that slope-normal slab displacement was required for fracture propagation on low-angle terrain. They proposed that compressive failure of the weak layer could create a propagating, gravity-induced *flexural wave* in the slab (as described by Lackinger, 1989), which provided the excess stress to drive the fracture process. More recently, Heierli (2005) modeled a theoretical solitary flexural wave propagating in a layered snowpack, and was able to reproduce the experimental results of Johnson (2001) precisely. Whereas the fracture mechanical models do not include a compressive component, these models *require* one. Heierli (2005) calculated a characteristic length of approximately 89 cm over which this collapse occurs, based on snowpack properties reported for Johnson and others' (2004) experiment.

Most of the common small-column snowpack stability tests utilize a 30 cm × 30 cm vertical isolated column, which is similar in horizontal surface area to some loading

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apparatus such as a shovel blade in compression tests (Jamieson, 1999), or more specialized apparatus such as the rammrutsch (Schweizer and others, 1995) or 'drop-hammer' (Stewart, 2002). Loading a test column in this fashion will limit the contribution of a flexural wave in the slab to the fracture process because the 'wavelength' of the vertical slab displacement may be of the order of 1 m (Heierli, 2005). In addition, the two-dimensional extent of the fracture area in these small-column tests is close to the smallest estimate of α_c for self-propagation of fractures (Schweizer and others, 2003). While possibly appropriate for measuring implicitly the energy required to fracture a known area, this geometry is probably insufficient to observe fractures propagating independent of trigger energy as they do in slab avalanche release. A test for fracture propagation, therefore, should allow for the unhindered development of flexural waves in the slab. In the test method presented here, by extending the downslope dimension of the isolated column to a length greater than the approximate wavelength over which slab bending occurs, we modify the small-column stability test configuration to allow a flexural wave in the slab to develop following the initiation of fractures.

Based on recent insights into the fracture process (e.g. Schweizer and others, 1995; Johnson and others, 2004; Van Herwijnen, 2005), we attempt to improve the common stability test configuration such that it becomes a closer proxy for the weak-layer fracture process in natural or human-triggered avalanches. We are developing a practical field test for the fracture propagation propensity of weak snowpack layers. In this paper, we introduce the two current versions of the fracture propagation test, and report results of testing conducted in the Columbia Mountains of British Columbia, Canada, during the winter of 2005.

METHODS

Figure 1 shows the schematic design of the prototype propagation test. A vertical column measuring 30 cm across slope by approximately 3 m downslope is isolated to a depth below the weak layer of interest (Fig. 1a). The up-slope edge of the column is dynamically loaded to fracture using a drop-hammer apparatus, as described by Schweizer and others (1995), Stewart (2002) and Campbell (2004). The apparatus consists of a 30 cm × 30 cm stiff plastic plate, onto which a 1 kg brass weight is dropped from known heights along a steel guide-rod (Fig. 1b and c). We collected most of our results in 2005 using one of two distinct impact configurations, one with the impact plate resting on a horizontal platform 15 cm above the weak layer, measured on the up-slope edge of the column (Fig. 1b), and another with the impact plate resting on the often inclined surface (Fig. 1c). For the configuration shown in Figure 1b, a horizontal saw cut (no snow removed) extending from the plate edge to the snow surface reduces stress concentrations and fracturing of the slab at the downslope corner of the plate. The surface impact configuration (Fig. 1c) allowed us to initiate and observe fractures in shallow buried weak layers. In both cases, the column extends for up to 3 m in the downslope direction. Fractures in the weak layer initiate beneath the drop-hammer apparatus. Most often, we used an incremental drop sequence, beginning by dropping the weight from 5 cm above the impact plate and progressing in 5 cm increments until fracture. We recorded both the maximum drop height (h) and length of the fracture (l)

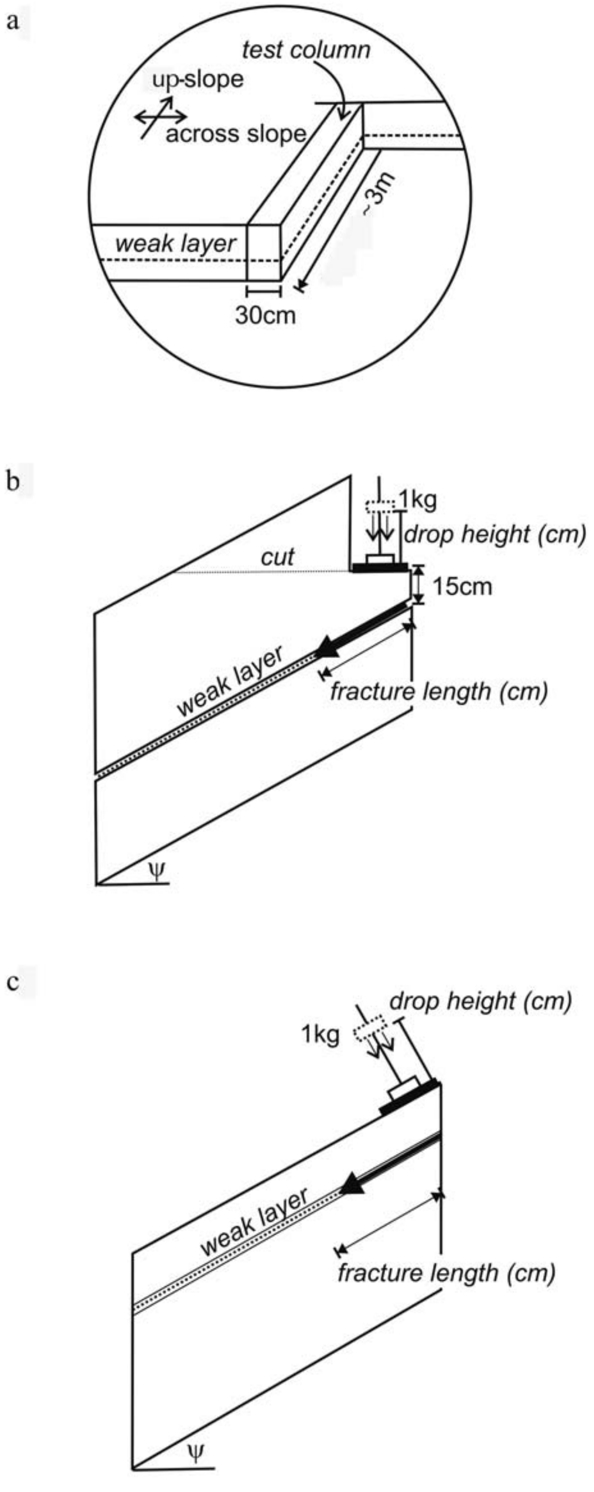

Fig. 1. Schematic of the propagation test method, showing (a) perspective view of the isolated column for the propagation test; (b) profile view of platform impact test configuration; and (c) profile view of surface impact test configuration, used to test shallow weak layers (thin slabs).

measured layer-parallel from the up-slope end (Fig. 1). In some cases, the slab fractures on the same loading step as initial weak-layer fracture, leading to arrest of the weak-layer fracture. In order to alleviate this, we sometimes used an alternative drop sequence, where the weight was dropped ten times from 5 cm, ten times from 10 cm and ten times from 15 cm, stopping when a fracture was

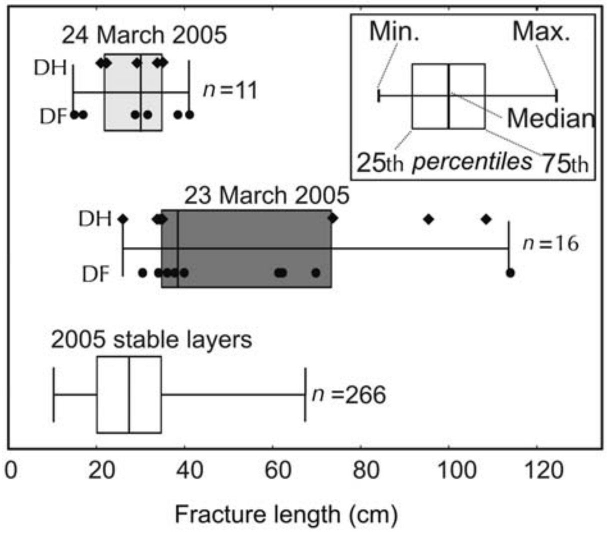

Fig. 2. Box-and-whiskers plot of fracture lengths for 2005 stable layers, 23 March 2005 and 24 March 2005 datasets. Individual data points shown for decomposing fragments layer (DF; filled circles) and depth hoar (DH; filled diamonds). Line, box and whiskers represent median, inter-quartile range and range, respectively, and *n* is the number of points in each dataset.

observed in the weak layer. In this drop sequence, the incremental weak-layer damage from the small impacts may lead to fracture in the weak layer while the slab remains intact.

Since other tests of snow columns, such as the rutsch-block test, correlate with nearby slab avalanching (Föhn, 1987a), we expect longer fracture lengths in our tests where local propagation potential is high (slab avalanching and 'whumpfs', i.e. rapidly propagating and collapsing fractures in weak layers on terrain not steep enough for avalanching, on nearby slopes), and lower drop heights where the strength of the weak layer is low. Here we include any conditions leading to fracture arrest as part of the propagation propensity of layer, and as such expect to observe some propagating fractures that meet an arrest condition within the column. We also expect that where weak-layer fractures are truly self-propagating, as they would be in a human-triggered avalanche, the fracture length should be independent of drop height, just as the width of slab avalanche size appears to be independent of the trigger energy (Jamieson and Johnston, 1992).

RESULTS

Researchers from the University of Calgary performed fracture propagation tests, using the techniques described above, during the winter of 2005 at field stations in the Columbia Mountains at Mount Fidelity in Glacier National Park (51°14′ N, 117°41′ W) and at Mount St Anne, near Blue River, British Columbia (52°16′ N, 119°17′ W). In addition, propagation testing was conducted at several locations in the Dogtooth Range outside the ski-area boundaries of Kicking Horse Mountain Resort, near Golden, British Columbia (51°17′ N, 117°05′ W). In total, we observed approximately 530 fractures, on 20 different days and nine different weak layers. The vast majority of observed fractures occurred in layers that *were not* involved in local or regional avalanche activity at the time of the test. This means that we have collected a large database of fracture observations from relatively *stable* layers, with only a few exceptions.

All the data presented here were collected using the surface loading configuration (Fig. 1c). For the 266 'stable' layers observed during most of the 2005 field season, fracture lengths ranged from 10 to 66 cm, with a median of 27.0 cm (Fig. 2). This stable dataset ($n = 266$) includes tests performed using both the 5 cm incremental ($n = 225$) and repeated drop sequences ($n = 41$) described above, as do the results presented below. We combined these datasets since we found no conclusive evidence that the fracture lengths with different drop sequences differed significantly (i.e. Mann–Whitney *U*-test: $z = 2.16$, $p = 0.03$; Wald–Wolfowitz runs test: $z = -1.34$, $p = 0.18$).

On 22 March 2005, a skier triggered a size 2 slab avalanche (large enough to bury, injure or kill a person; CAA, 2002) on a southeast-facing steep slope at ~2300 m elevation in the Dogtooth range. On 23 March 2005, another size 2 skier-triggered avalanche was reported with a similar aspect and elevation from the same ridgeline. While traveling on skis on southeast-facing slopes approximately 1 km away from the avalanche slopes, two field researchers triggered many whumpfs. Figure 2 shows the results of propagation testing from that area on 23 March 2005. Two weak layers fractured during testing: a non-persistent storm snow interface (0.3–0.5 mm decomposing fragments) buried 10–20 cm deep (DF), and a 0.8 cm thick layer of 1–1.5 mm depth hoar (DH; cupped and faceted crystals), buried 20–30 cm deep on top of a thick melt–freeze crust. This crust was buried on 26 January 2005. Results from 23 March 2005 are the only ones in the 2005 dataset that can be conclusively associated with local indications of high fracture propagation propensity, such as whumpfs and the occurrence of skier-triggered avalanches. In fact, whumpfs were so frequent in the area on this day that workers had to approach the study site very carefully to avoid fracturing the weak layer. Examination of Figure 2 shows that seven of 16 observed fractures were longer than 60 cm. Three of the seven observed fractures in the DH layer, believed to be the failure layer for the whumpfs and avalanche activity, were 75 cm or longer, with one fracture in excess of 1 m.

Figure 2 also shows the results of propagation testing performed on 24 March 2005. This study site was approximately 30 m from the previous site, and within 10° aspect, 2° slope incline and 10 m elevation. No fractures longer than 41 cm were observed on 24 March. No avalanche activity was reported from the area on 24 March 2005. Many of the slopes immediately adjacent to those that had slid in the previous 2 days were skied and none avalanched. In addition, despite many attempts, the field team caused no whumpfs on the slopes surrounding the test pit. Therefore, we are confident that propagation propensity of the DH layer was low on these slopes on 24 March 2005, rather than having fractured and re-bonded prior to testing.

These small datasets from 23 and 24 March 2005 in the Dogtooth Range indicate that longer fractures in this type of test were found when local conditions were suitable for fracture propagation. However, along with several long fractures on 23 March, half the fractures in both layers were <39 cm long, with a similar distribution to the results of 24 March. In fact, all of the fracture lengths collected on 24 March, as well as 50% of the data from 23 March, are below the 85th percentile of the 2005 dataset for

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identical test methods ($n = 266$). The longer fractures (i.e. FL > 62 cm, $n = 7$) from 23 March 2005 are greater than the 99th percentile of the 2005 dataset, with five fractures well outside the range of 'stable' fracture lengths.

DISCUSSION

Without the 23 March 2005 results from the Dogtooth Range, the 2005 dataset would suggest that stable weak layers generally produce initial fractures around 30 cm long for a range of drop heights, based on the median for the 2005 dataset of 27 cm, with 50% of the fracture lengths between 20 and 34 cm. However, on 23 March 2005, when there were local indications of high fracture propagation propensity, the distribution of fracture lengths was bimodal, with one group similar to data collected on stable weak layers, and another group of much longer fractures, all greater than the 99th percentile or outside the range of the 2005 dataset. This bimodality of fracture lengths may not be trivial; 50% of fractures observed in 2005 lie between 22 and 35 cm. Even in snowpacks known to be unstable, a common grouping of fracture lengths lies conspicuously close to the 30 cm dimension of the impact plate (Figs 1 and 2). Further research is required to assess the possible dependency of fracture length on the test techniques and apparatus. For example, increasing or decreasing the size of the impact plate would allow unambiguous evaluation of the effect of plate size on fracture length. One possible explanation is that in cases where the propagation propensity of a layer is low, or where it is difficult to achieve a state of self-propagation, the energy from the impact of the hammer is solely responsible for the fracturing of the weak layer. In this case, the impact-induced dynamic stress, which is concentrated directly below the impact plate, causes fracture of the weak layer where peak stress overcomes strength, and not beyond. However, in the 2005 dataset where the platform loading configuration, rather than the surface loading configuration, was used ($n = 134$) we projected the 30 cm horizontal dimension of the impact plate onto the weak layer plane, and compared this to the first fracture length for the same tests. There is no significant correlation between the plate dimension and fracture length ($R = -0.0647$, $p = 0.457$). This analysis may have included fracture lengths with varying relationships to the plate size. Therefore, the relationship between the plate dimension and the dynamic stress arriving at the weak layer(s) may not be straightforward.

Jamieson and Johnston (1992) presented a fracture arrest model for unconfined slab avalanches that relates slab thickness and tensile strength, along with basal shear strength, to the extent of the release area. In their model, arrest of the propagating weak-layer fracture is directly related to elastic strain energy released by tensile fracturing in the slab, and the weak-layer fracture propagates as long as its progress is ahead of the tensile fracture. Often, we observed this phenomenon during propagation testing, where a vertical or inclined fracture through the slab, commonly initiated at the downslope edge of the impact plate, intercepted and arrested the weak-layer fracture. In other cases, however, the fracture in the weak layer arrested with no obvious sign of damage or failure in the slab. Rarely, we observed several evenly spaced slab fractures that extended from the snow surface under the plate but did not reach the weak layer and that did not cause the arrest of the propagating weak-layer fracture. Van Herwijnen (2005, p. 245–8) describes the same phenomenon in plan view ('en echelon' fractures) for releasing slab avalanches. With careful observations of snowpack properties and the arrest of fractures during testing, we may be able to better understand the relationship between failure or fracture of the slab and the propagating weak-layer fracture.

CONCLUSIONS

The fracture propagation test method presented here is the first designed to test snow slabs and weak layers specifically for fracture propagation propensity, and has several advantages, both as a research tool and as a practical test method:

It allows for the development of a flexural wave in the slab, coupled with collapse of the weak layer (as proposed by Johnson (2001) and Van Herwijnen (2005) for slab failure) better than standard small-column test methods;

A small dataset from a single day suggests that the downslope layer-parallel length of fractures induced by this test may be much longer where local conditions clearly indicate high propagation propensity of the local snowpack. Collecting more test results under such conditions is a priority of upcoming field campaigns.

Through the course of testing in 2005, several potential problems with this technique have arisen. It seems that regardless of local snowpack conditions, there is a clear tendency for fracture lengths to be between approximately 20 and 35 cm. This length is close to the dimension of the test apparatus (impact plate) and suggests that some fracture lengths may be dependent on the test apparatus, even where indications of locally high fracture propagation propensity exist.

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REFERENCES

Bažant, Z.P., G. Zi and D.M. McClung. 2003. Size effect law and fracture mechanics of the triggering of dry slab snow avalanches. *J. Geophys. Res.*, **108**(B2), 2119–2229.

Broek, D. 1982. *Elementary engineering fracture mechanics. Third edition*. The Hague, Martinus Nijhoff Publishers.

Campbell, C.P. 2004. Spatial variability of slab stability and fracture properties in avalanche start zones. (MSc thesis, University of Calgary.)

Canadian Avalanche Association (CAA). 2002. *Observation guidelines and recording standards for weather, snowpack, and avalanches*. Revelstoke, Canadian Avalanche Association.

Faillettaz, J., D. Daudon, D. Bonjean and F. Louchet. 2002. Snow toughness measurements and possible applications to avalanche triggering. *In* Stevens, J.R., *ed. International Snow Science Workshop 2002, 29 September–4 October 2002, Penticton, British Columbia. Proceedings*. Victoria, British Columbia Ministry of Transportation. Snow Avalanche Programs, 540–543.

Föhn, P. 1987a. The 'rutschblock' as a practical tool for slope stability evaluation. *In* Salm, B. and H. Gubler, *eds. Avalanche formation, movement and effects*. Wallingford, Oxon., International Association of Hydrological Sciences, 223–228. (IAHS Publication 162.)

Föhn, P. 1987b. The stability index and various triggering mechanisms. *In* Salm, B. and H. Gubler, *eds. Avalanche formation, movement and effects*. International Association of Hydrological Sciences, 195–211. (IAHS Publication 162.).

Heierli, J. 2005. Solitary fracture waves in metastable snow stratifications. *J. Geophys. Res.,* **110**(F2), F02008. (10.1029/2004JF000178.)

Jamieson, J.B. 1999. The compression test – after 25 years. *Avalanche Review,* **18**(1), 10–12.

Jamieson, J.B. and C.D. Johnston. 1992. A fracture-arrest model for unconfined dry slab avalanches. *Can. Geotech. J.,* **29**(1), 61–66.

Jamieson, J.B. and C.D. Johnston. 1998. Refinements to the stability index for skier-triggered dry-slab avalanches. *Ann. Glaciol.,* **26**, 296–302.

Johnson, B.C. 2001. Remotely triggered slab avalanches. (MSc thesis, University of Calgary.)

Johnson, B.C., B. Jamieson and R. Stewart. 2004. Seismic measurement of fracture speed in a weak snowpack layer. *Cold Reg. Sci. Technol.,* **40**(1–2), 41–45.

Kirchner, H., G. Michot and T. Suzuki. 2000. Fracture toughness of snow in tension. *Philos. Mag. A,* **80**(5), 1265–1272.

Kirchner, H., G. Michot and J. Schweizer. 2002a. Fracture toughness of snow in shear and tension. *Scripta Mater.,* **46**(6), 425–429.

Kirchner, H., G. Michot and J. Schweizer. 2002b. Fracture toughness of snow in shear under friction. *Phys. Rev. E,* **66**(2), 027103. (10.1103/PhysRevE.66.027103.)

Lackinger, B. 1989. Supporting forces and stability of snow-slab avalanches: a parameter study. *Ann. Glaciol.,* **13**, 140–145.

McClung, D.M. 1979. Shear fracture precipitated by strain softening as a mechanism of dry slab avalanche release. *J. Geophys. Res.,* **84**(B7), 3519–3526.

McClung, D.M. 1981. Fracture mechanical model of dry slab avalanche release. *J. Geophys. Res.,* **86**(B11), 10,783–10,790.

McClung, D.M. 1987. Mechanics of snow slab failure from a geotechnical perspective. *In* Salm, B. and H. Gubler, *eds. Avalanche formation, movement and effects*. International Association of Hydrological Sciences, 475–508. (IAHS Publication 162.)

Perla, R. and T.M.H. Beck. 1983. Experience with shear frames. *J. Glaciol.,* **29**(103), 485–491.

Roch, A. 1966. Les variations de la résistance de la neige. *In Proceedings of the International Symposium on Scientific Aspects of Snow and Ice Avalanches*. Gentbrugge, Belgium, International Association of Scientific Hydrology, 86–99. (IASH Publication 69.)

Schweizer, J. 1999. Review on dry snow slab avalanche release. *Cold Reg. Sci. Technol.,* **30**(1–3), 43–57.

Schweizer, J., M. Schneebeli, C. Fierz and P.M.B. Föhn. 1995. Snow mechanics and avalanche formation: field experiments on the dynamic response of the snow cover. *Surv. Geophys.,* **16**(5–6), 621–633.

Schweizer, J., J.B. Jamieson and M. Schneebeli. 2003. Snow slab avalanche formation. *Rev. Geophys.,* **41**(4), 1016. (10.1029/2002RG000123.)

Schweizer, J., G. Michot and H.O.K. Kirchner. 2004. On the fracture toughness of snow. *Ann. Glaciol.,* **38**, 1–8.

Sigrist, C., J. Schweizer, H. Schindler and J. Dual. 2005. On size and shape effects in snow fracture toughness measurements. *Cold Reg. Sci. Technol.,* **43**(1–2), 24–35.

Stewart, K. and J.B. Jamieson. 2002. Spatial variability of slab stability in avalanche start zones. *In* Stevens, J.R., *ed. International Snow Science Workshop 2002, 29 September–4 October 2002, Penticton, British Columbia. Proceedings*. Victoria, British Columbia Ministry of Transportation. Snow Avalanche Programs, 544–548.

Van Herwijnen, A.F.G. 2005. Fractures in weak snowpack layers in relation to slab avalanche release. (PhD thesis, University of Calgary.)

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