

AVALANCHE RELEASE 101

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ABSTRACT: Our understanding of dry-snow slab avalanche release improved over the last decade – not the least by consistently following a fracture mechanical approach. Whether we consider artificial triggering or natural release, slab avalanches result from a sequence of fracture processes including (i) failure initiation in a weak layer underlying a cohesive snow slab, (ii) the onset of crack propagation, (iii) dynamic crack propagation through the weak layer across the slope, and (iv) tensile failure – equivalent to crack arrest, followed by sliding of the slab. While failure initiation is best understood in terms of applied stress and strength, crack propagation is best understood in terms of stress intensity and fracture toughness. The typical anisotropic microstructure of persistent weak layers favors failure in shear rather than compression under mixed-mode loading – though the failure type at the micro-scale is largely unknown due to the complex stress state in the ice matrix. The fracture mechanical approach has also changed our view on the spatially variable nature of the snow cover. Spatial variations of weak layer as well as slab properties may control avalanche formation, since disorder is fundamental for the fracture process. For example, failures will initiate from locally weaker spots, and fractures may arrest due to locally stronger areas. Whereas we still lack a comprehensive model linking damage at the micro-scale to avalanche size, recent modelling approaches have demonstrated – by assuming realistic failure behavior of the weak layer including its collapse and resulting mixed stress states in the slab layers – that not only failure initiation, but also crack propagation depends on slope angle. We present a modern synthesis of avalanche release.

KEYWORDS: snow failure, failure initiation, crack propagation, avalanche formation, avalanche release, fracture mechanics

1. INTRODUCTION

Snow avalanches range among the most prominent natural hazards which threaten people living and travelling in mountain regions. Avalanche warning services therefore issue public avalanche bulletins to warn the general public. However, the ability to forecast avalanches, i.e. predicting snow instability in time and space (McClung 2000), is hampered by our limited understanding of avalanche release. Avalanche release is essentially a fracture process in snow – a material unlike others. Snow exists close to its melting point, is extremely porous and highly compressible. The mechanical behavior of snow is therefore strongly rate-dependent and structural collapse readily occurs during fracture.

As dry-snow slab avalanches represent the main threat to people and infrastructure, we will in the

following only focus on the formation of this type of avalanche (Figure 1). Such avalanches result from a sequence of fracture processes including (i) failure initiation in a weak layer underlying a cohesive snow slab, (ii) the onset of crack propagation,



Fig. 1: Dry-snow slab avalanche

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(iii) dynamic crack propagation through the weak layer across the slope, and (iv) tensile failure followed by sliding of the slab (Figure 2) (e.g., McClung 1979; Schweizer et al. 2003; van Herwijnen and Heierli 2009).

While failure initiation is best understood in terms of applied stress and strength, crack propagation is best understood in terms of stress intensity and fracture toughness (McClung and Schweizer 1999). The release of a slab avalanche is therefore a fracture mechanical problem and both strength and fracture toughness are mechanical properties that depend on temperature, density, and microstructure (e.g., Hagenmuller et al. 2014; Schweizer et al. 2004).

In fracture mechanics there are two alternative approaches – equivalent under certain circumstances: the stress intensity approach (as mentioned above), and the energy criterion. The energy approach considers the balance between the energy available for crack growth (i.e. for fracture) and the energy required to overcome the resistance of the material. The material resistance, also called specific fracture energy, includes the surface energy, i.e. the energy to create two new surfaces, as well as other types of energy dissipation associated with crack propagation (Anderson 2005).

Fracture processes in a stratified snow cover must be described by considering crack propagation in a multilayered elastic system under mixed-mode loading (Hutchinson and Suo 1992). However, this

is a complex problem and presently not amenable for solving practical problems such as avalanche release.

Hence, the avalanche release problem is usually simplified to a three-layer system consisting of a slab, a weak layer and a base. One then considers failure initiation in the weak layer underlying the slab followed by crack propagation along the weak layer. Failure initiation requires the formation of a localized failure due to damage accumulation at the scale of the bonds between the snow crystals. At the edges of this initial crack, stress concentrations occur as the load of the overlying slab layers is no longer fully supported. In the past, this part of the weak layer that has failed has often been termed deficit zone (Conway and Abrahamson 1984). With crack growth, stress concentrations increase and once they overcome the fracture toughness, rapid crack propagation starts. This is the stress intensity approach. In the energy approach, the onset of rapid crack propagation depends on whether sufficient deformation energy stored in the system can be released to overcome the specific fracture energy of the weak layer. The size of the initial crack when the energy released due to an incremental advance of the crack equals the energy required to advance the crack (i.e. the crack resistance) is called critical crack length. Once the critical crack length is reached, rapid, dynamic crack propagation along the weak layer, across the slope, starts. The critical crack length is hence an instability criterion – crucial for snow slope instability evaluation.

Dry-snow slab avalanche release

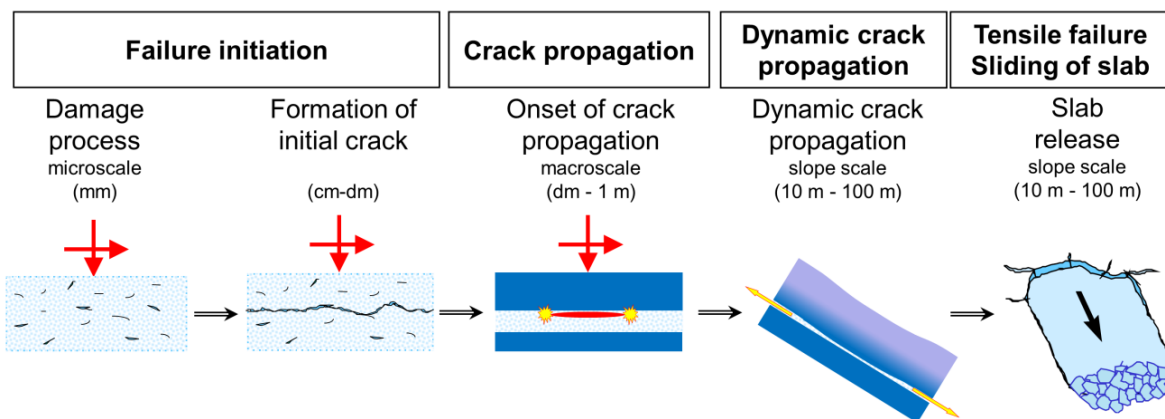


Fig. 2: Conceptual model of dry-snow slab avalanche release including the four stages of (i) failure initiation in a weak layer underlying a cohesive snow slab, (ii) the onset of crack propagation, (iii) dynamic crack propagation through the weak layer across the slope, and (iv) tensile slab failure arrests the propagating crack in the weak layer, followed by sliding of the slab; red arrows indicate mixed-mode loading (adapted from Schweizer et al., 2003).

Thanks to various laboratory, field and modeling studies our understanding of the above sketched view of avalanche release has improved over the last decade since the conceptual model of slab release (Figure 2) was suggested by Schweizer et al. (2003). In the following, we try to summarize some of these recent findings with regard to the four stages of avalanche release mentioned above.

2. FAILURE INITIATION – SNOW FAILURE

The first stage of avalanche release, failure initiation, covers the formation of an initial macroscopic crack, which might reach the critical size for crack propagation. Before we review the characteristics of snow failure, we first consider the type of loading since in the first, and only the first, stage of avalanche release there is a difference between natural release and artificial triggering.

In the case of natural release, the formation of this initial failure occurs at the microscale – and needs some time (presumably minutes to hours). The two mentioned scales, microscopic and macroscopic, are defined as the scale of bonds and crystals (0.1 to 1 mm), and the scale of the slab (or snowpack) thickness (0.1 to 1 m), respectively. In the case of artificial triggering by, for instance, a skier, an initial failure of macroscopic size in the weak layer is directly induced by the rapid, localized load due to the weight of the skier moving on top of the snowpack. In the case of natural release, the external loading which increases the deformation rate within the weak layer is slow. The major difference between natural release and artificial triggering is therefore the loading rate and how the initial failure arises. Importantly, the strength of snow depends on the loading rate.

Indeed, various laboratory studies have shown that the mechanical behaviour of snow is highly rate-dependent, in other words, that the strength of snow decreases with increasing strain rate and temperature. The ductile-to-brittle transition occurs at a strain rate of about 10^{-3} to 10^{-4} s $^{-1}$ (Fukuzawa and Narita 1993; McClung 1977; Narita 1980; Reiweger et al. 2010; Schweizer 1998). Since snow generally exists at temperatures close to its melting point, Schweizer (1999) suggested the rate-dependent behaviour to be a consequence of two competing processes: damage (breaking of bonds) and sintering (creation and strengthening of bonds) (Podolskiy et al. 2014; Szabo and Schneebeli 2007; van Herwijnen and Miller 2013). In fact, Reiweger et al. (2009) reproduced the rate dependence of snow strength with a fiber bundle

model including the two competing processes of bond breaking and sintering by assigning different typical times to failure and healing. Hence, when deformation increases, e.g. due to loading or warming (Reuter and Schweizer 2012), the damage process may dominate, i.e. more bonds break than new bonds form: a localized initial failure may develop. This increase of failure events (bond breaking) with ongoing damage prior to fracture manifests itself by acoustic emissions (Reiweger et al. 2015b).

In a sloping snow cover that deforms due to gravity the snow microstructure constantly changes due to snow metamorphism and due to constant bond breaking and re-bonding – as in snow settlement (Schleef et al. 2014). Microstructural changes already occur at very small deformations, larger than about 0.5 to 5×10^{-4} (Camponovo and Schweizer 2001). Only smaller deformations are fully recoverable and no structural change occurs. In a stratified snow sample, the deformation process is concentrated in weak layers (e.g., Reiweger and Schweizer 2010), layers within the snowpack that have distinct properties, in particular lower density and lower elastic modulus than the adjacent layers above and below (Köchle and Schneebeli 2014). In addition, weak layers often have a strongly anisotropic microstructure as their crystals generally were grown under strong temperature gradients. They typically include faceted crystals, depth hoar and surface hoar crystals, also called persistent grain types (Jamieson 1995). Due to their anisotropic microstructure their mechanical behavior depends on the loading direction. Walters and Adams (2014) showed that the faceting process results in a large increase in vertical stiffness and a decrease in shear stiffness. Furthermore, the strength of layers of buried surface hoar is lower in shear than in compression (Reiweger and Schweizer 2010). This finding has subsequently been confirmed for weak layers consisting of faceted crystals and depth hoar (Reiweger and Schweizer 2013). The observed failure behaviour of these weak layers can be described with a modified Mohr-Coulomb model accounting for the possible compressive failure of snow. This new mixed-mode shear-compression failure criterion can be used in avalanche release models (Reiweger et al. 2015a).

The dependence of strength on load direction is of particular relevance for the initiation of naturally (spontaneously) releasing avalanches. Weak layers on a slope are loaded by the weight of the overlying layers, so under mixed compressive

and shear load with the compressive load always dominating below 45° . Nevertheless, due to the lower strength in shear, for natural avalanches this means that the initial failure is caused by shear rather than compressive deformation, in other words that steep terrain favors the damage process leading to the formation of an initial crack.

Hence, under most conditions snow failure under mixed-mode loading is due to shear failure. However, when considering the microstructure of snow, high local stress concentrations may occur (Schneebeli 2004) leading, e.g., to tensile failure. In other words, at the scale of bonds, any failure mode seems possible (Schweizer and Jamieson 2008). In this context, it is important to note that the collapse of weak layers that is observed after failure follows from the structural damage in the highly porous microstructure of weak layers during crack propagation (Figure 3). Collapse is not a failure mode but a consequence of failure. The fact that there is vertical displacement does by no means imply that there was a compressive failure¹.



Fig. 3: This photograph of a collapsed surface hoar layer is probably the most influential and has triggered many ideas and debates over the last 15 years (from Jamieson and Schweizer 2000).

Localized loading by a skier will always induce shear and normal stresses even in flat terrain. Indeed, the skier induced shear stress in the flat is still about one third of the normal stress, and only

¹ Weak layer collapse is similar to the so-called pancake failure of buildings due to an earthquake. Ground motion due to an earthquake causes shaking of the house. The lateral forces cause side-to-side swaying; eventually the columns fail and the floors collapse one atop each other. Hence, collapse is not due to vertical load, but lateral forces (e.g., Bachmann 2002).

about 33% lower than on a 38° slope (Figure 4; Das 1983). Considering the strong dependence of strength on load direction it seems very plausible that even in the flat the skier's shear stress causes weak layer failure – given that the compressive strength is about an order of magnitude larger than the shear strength (Jamieson and Johnston 2001; Shapiro et al. 1997).

The stress due to the additional load by a skier strongly decreases with depth and depends on slab layering; hard layers tend to distribute and hence decrease the stress at a given depth («bridging») (Habermann et al. 2008; Thumlert and Jamieson 2014). The skier stress has been introduced into the stability index (Föhn 1987), the traditional strength-of-material approach (Roch 1966), and recently an improved formulation that accounts for slab layering has been proposed (Monti et al. 2016).

With regard to natural release vs. artificial triggering, we recall that in both cases an initial failure of macroscopic size is needed. The main difference is the rate of loading implying different failure processes leading to the initial crack. In the case of natural release, the initial failure is the result of a microscopic (initially probably diffuse) damage process, whereas the macroscopic failure (or initial crack) in the case of artificial triggering is directly due to the local overload (brittle failure).

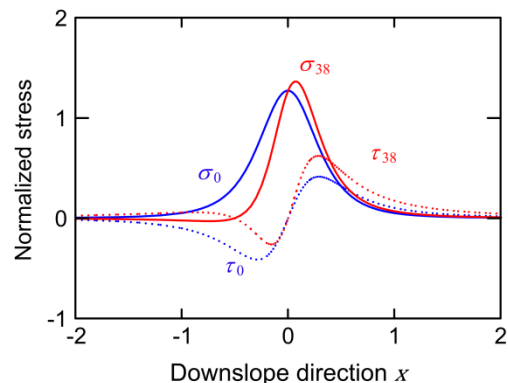


Fig. 4: Normal (solid line) and shear stress (dotted line) due to a skier, normalized by line load, for a 38° slope (in red) and for flat terrain (in blue), for a depth of $h = 0.5$ m.

Once an initial crack has formed it may under continued loading grow (subcritical growth) until reaching its critical size – or growth may stop and the crack may heal and stability increases (Birkeland et al. 2006). In the next section, we consider the conditions for the onset of rapid crack propagation.

3. CRACK PROPAGATION – CRITICAL CRACK SIZE

Crack propagation is the second stage in dry-snow slab avalanche release. Whereas failure initiation can be assessed by strength-of-material approaches, for example, a stability index, the failure criterion for crack propagation is the flaw size, or critical crack size. For a given material it depends on the applied load as well as the crack resistance or specific fracture energy, the analogue to strength.

As can readily be seen in a propagation saw test (Gauthier and Jamieson 2006; Sigrist and Schweizer 2007; van Herwijnen and Jamieson 2005) where we artificially create the initial crack by cutting along the weak layer, at a certain crack length the crack suddenly shoots across the column.

In a brittle isotropic material, this critical crack length r_c can be expressed as $r_c \propto \frac{Ew_f}{\pi\sigma^2}$ (Anderson 2005). Thus, the relevant properties with respect to the onset of crack propagation are the elastic modulus E , the specific fracture energy w_f , and the applied stress σ .

However, evaluating the critical crack length for cracks in a natural stratified snow cover with the above relation is not readily possible – not the least since the material properties involved are not well known. Several simplifying assumptions are needed to model avalanche release. For example, McClung (1979), Chiaia et al. (2008) and Gaume et al. (2014) assumed an infinitely thin weak layer (i.e. an interface) so that the problem can be solved in one direction only (down-slope), thereby neglecting the structural collapse of the weak layer which causes bending of the overlaying slab. Heierli et al. (2008), on the other hand, assumed a weak layer of finite thickness with a slope-independent failure criterion. Further assumptions include the weak layer to be rigid which allowed neglecting the elastic mismatch between the slab and the weak layer.

In interfacial fracture mechanics (Hutchinson and Suo 1992), the elastic mismatch describes the difference in material properties between the two layers where the fracture occurs. Crack propagation propensity should increase with, for example, increasing difference in hardness across the layer interface (Schweizer and Camponovo 2001). In fact, large hardness differences were found to be related to critical weak layers and skier-triggering probability (Schweizer and Jamieson 2007; van Herwijnen and Jamieson 2007).

More recently, Gaume et al. (2016c) developed a new formulation for evaluating the critical cut length based on discrete element simulations of the propagation saw test. The new formulation considers the mechanical behavior of the weak layer, the mixed stress states in the slab induced by slab tension and bending resulting from the structural failure (collapse) of the weak layer, and the complex interplay between slab and weak layer elasticity (elastic mismatch). In contrast to the anticrack model (Heierli et al. 2008) it predicts that the critical crack length decreases with increasing slope angle – a rather intuitive result. Still the model allows for crack propagation in flat terrain in the context of remote triggering – it reconciles the shear- and collapse-based approaches (Gaume et al. 2016b).

As mentioned above, the propagation saw test is the ideal test to assess whether an initial crack in a weak layer will propagate or not. Obviously, as we artificially introduce a saw cut so that the slab is no longer supported and starts bending, this configuration may not fully represent the natural situation in avalanche release where an initial crack forms from damage. It is expected that the slab will be supported to some extent prior to the onset of crack propagation and the effects of slab bending are smaller than in a PST (McClung and Borstad 2012). Still the PST has extensively been validated and test results are well related to signs of instability such as whumpfs, shooting cracks and recent avalanching (e.g., Gauthier and Jamieson 2008).

Furthermore, the PST is the only snow instability test that is amenable to quantitative analysis, either by finite element modelling (Sigrist and Schweizer 2007), discrete element modeling (Gaume et al. 2015b) or by evaluating the analytical expression for the crack energy of the PST system as described by Heierli et al. (2008). To get the required mechanical properties for the latter approach, PST experiments are recorded with a video camera to obtain the displacement field of the slab using particle tracking velocimetry (PTV; van Herwijnen et al. 2010; van Herwijnen et al. 2016a).

In recent years, the PTV method has provided great insight, in particular, into weak layer fracture and crack face friction (van Herwijnen et al. 2016a). From analyzing the bending of the overhanging part of the slab, the effective elastic modulus as well as the specific fracture energy of the weak layer can be determined – hence two of the crucial mechanical properties to evaluate the criti-

cal cut length, which alternatively can only be estimated from the SMP penetration resistance (Reuter et al. 2015a). van Herwijnen et al. (2016a) report that the effective elastic modulus ranged from 0.08 to 34 MPa and increased with increasing density. These values are in good agreement with previous laboratory measurements in the same range of strain rates. The values for specific fracture energy of the weak layer varied between 0.08 and 2.7 J m⁻². Compared to the fracture energy of ice many of these values seem unrealistically high. The observed discrepancy suggests that the mechanical properties obtained via PTV analysis of PSTs have to be considered as effective values. The observed displacement field very likely is not only the result of elastic deformation and a potential fraction of the change in potential energy observed during a PST is dissipated and may not be available for driving crack advance.

With regard to the absolute values of the critical crack size in avalanche release, most PST results show crack lengths between 20 and 40 cm, or in general $r_c/D \leq 1$. The crack size at the onset of rapid crack propagation is particularly relevant to assess the effect of snowpack variability on avalanche formation (Kronholm and Schweizer 2003). The critical crack lengths frequently observed in PSTs support previous estimates of the critical crack size of the initial failure, namely less than about 1 m² (Bazant et al. 2003; McClung and Schweizer 1999; Schweizer et al. 2004). The spatial effect of a skier is of the same order (Schweizer and Camponovo 2001), supporting the estimate, since skiers frequently induce an initial failure that is large enough for rapid self-propagation. It is not clear how frequently the skier-induced initial crack is too small for spontaneous crack propagation. Since the skier moves, this scenario seems rather unlikely, but it has been observed in the case of a skier tested slope (van Herwijnen and Jamieson 2005). Gaume et al. (2016a) suggested a new criterion for the onset of crack propagation in a weak snow layer below a cohesive snow slab in presence of an additional line load corresponding to a skier. In the case of natural avalanche release, the critical crack length may well be longer, in the range of 1 to 10 m (McClung and Schweizer 1999).

4. DYNAMIC CRACK PROPAGATION – TENSILE FAILURE – SLAB RELEASE

After the onset of crack propagation, the third and fourth stage in snow slab avalanche release include dynamic crack propagation within the weak layer across the slope until a tensile crack opens

up leading to crack arrest along the weak layer – followed by sliding of the slab, provided friction between the slab and the fractured weak layer is overcome.

Dynamic crack propagation deals with how far a running crack will propagate and ultimately determines avalanche size. Compared to the onset of crack propagation much less is known about this phase in slab release. During dynamic crack propagation the crack size is an unknown function of time, and material resistance to crack propagation generally increases with crack speed. As the excess energy is converted to kinetic energy, inertial effects become important; the magnitude of the kinetic energy dictates the crack speed (Anderson 2005). Furthermore, the roughness of crack faces increases with increasing crack speed (Gross and Seelig 2001) probably related to the accompanying change in mode-mixity. Thus, during dynamic crack propagation the crack speed is an important parameter.

For a uniform snow stratigraphy, the speed of propagating cracks is theoretically limited to a fraction of the shear wave speed (McClung 2005), which for a shear modulus of, for instance, 10 MPa and a snow density of 200 kg m⁻³ is about 200 m s⁻¹. This value has to be considered as an upper limit since for other materials crack propagation speeds never exceed 0.3 to 0.6 times the shear wave speed (Ravi-Chandar 2004). Crack propagation speeds in snow are therefore expected to be less than about 100 m s⁻¹.

Prior to 2000, there were no field measurements on dynamic crack propagation in snow. Several observations of firm quakes and whumpfs were reported and described as a collapsing wave that can travel over large distances (Benson 1962; DenHartog 1982; Truman 1973). Speed estimates ranged from 6 m s⁻¹ (Truman 1973) to slightly lower than the speed of sound in air (DenHartog 1982). The first reported crack speed measurement was carried out using seismic sensors positioned on the snow surface to measure the displacement of the slab during crack propagation (Johnson et al. 2004). After a whumpf was successfully triggered by a person on snow-shoes, the propagation speed was calculated to be 20 m s⁻¹. Since this first measurement, PTV has been used in combination with high-speed photography of fracture mechanical field experiments to investigate the displacement of the slab during dynamic crack propagation (van Herwijnen and Jamieson 2005; van Herwijnen and Birkeland 2014; van Herwijnen et al. 2010).

In fact, during a PST we observe the very beginning of dynamic crack propagation and also that cracks may arrest and slab failures occur. Though the length of a PST seems not sufficient to assess how far a running crack will propagate, PTV analysis of PST experiments has also provided insight into this initial phase of dynamic crack propagation. During dynamic crack propagation the weak layer gradually collapses. van Herwijnen et al. (2016b) reported a median collapse height of 3.6 mm. Crack propagation speeds were on the order of 10 to 30 m s⁻¹. For the collapse height as well as for the crack speed higher values were observed in tests where the crack propagated to the end of the column. These findings suggest that both weak layer collapse height and crack propagation speed may be indicative of how far cracks propagate.

It is presently unclear whether dynamic crack propagation can be described as the propagation of a flexural or bending wave as, for instance, proposed by Johnson et al. (2004).

When we observe a slab fracture in a PST, the crack arrested. This is most likely the case when the slab tensile strength is not sufficient as the bending stress increases during dynamic crack propagation (Gaume et al. 2015b; Schweizer et al. 2014). Therefore, complementing the failure initiation and crack propagation criteria with a third instability criterion related to the tensile strength of the slab seems very promising (Reuter et al. 2016a).

During the fourth stage, the slab becomes fully detached and starts sliding downslope. During this phase, it is mainly the friction between the slab and the broken weak layer (and/or the substratum) that determines whether an avalanche releases or the slope only fractures. The friction angle above which the slab will slide downslope, can also be determined with PTV analysis of PST experiments. Interestingly, the median coefficient of friction was 0.58 corresponding to a slope angle of 30° (van Herwijnen and Heierli 2009; van Herwijnen et al. 2016b). The highest values were obtained for weak layers of storm snow suggesting that the critical slope angle for avalanche release depends on weak layer type (McCammon 2009).

5. SPATIAL VARIABILITY

Our inability to predict snow slab avalanche release in time and space is mainly due to the multiscale variability of the quantities involved in avalanche release and the complex microstructure of snow (Gaume et al. 2014). This spatial variability

is due to several external drivers such as precipitation, wind or solar radiation, and their interaction with terrain and internal processes such as snow metamorphism or water infiltration. Understanding and predicting avalanche release under such multiscale spatial variations is extremely complex, and they hinder deterministic modeling of avalanche release.

Numerous field studies have documented spatial variations of snow cover properties (e.g., Birkeland et al. 1995; Jamieson and Johnston 1993; Landry et al. 2004). Initially, the research focus was mainly on assessing the reliability of snow stability measurements. More recently it has been recognized that spatial variations of slab and weak layer properties play an important role in the fracture processes of failure initiation and crack propagation (Schweizer et al. 2008). Still, the link between snowpack spatial variability and slope stability has not yet been established (Bellaire and Schweizer 2011; Schweizer and Reuter 2015). However, some of the external drivers of basin-scale snow instability variations have been identified (Reuter et al. 2015b) and output of high resolution numerical snow cover modeling has been shown to partially relate to measured patterns of snow instability (Reuter et al. 2016b).

On the other hand, numerical simulations allow assessing the effect of spatial variations on avalanche release probability (Faillietaz et al. 2004; Fyffe and Zaiser 2004, 2007; Kronholm and Birkeland 2005). Albeit based on simplified assumptions these model calculations help to conceptually understand the effect of spatial variations on slope stability. More recently, Gaume et al. (2014) applied stochastic-finite element simulations to model slope instability from weak layer heterogeneity. Their model considers spatial variations of weak layer shear strength and stress redistribution by the elasticity of the overlying slab. They demonstrated the knock-down effect on slope instability depending on three factors: (i) the ratio between the correlation length and the slab depth, (ii) the coefficient of variation of weak layer strength, and (iii) the elastic modulus of the slab.

With regard to dynamic crack propagation, Gaume et al. (2015a) extended the mechanically-based probabilistic model to analyse which snowpack parameters influence slab tensile failure propensity and, hence, the extent of the release area. They found that for thick and dense snow slabs, the tensile strength is sufficiently large so that the basal crack propagates across the entire slope and tensile failure through the slab occurs at topo-

graphical or morphological features – in other words topography rather than spatial variations in snow properties limited the avalanche size in their simulations. Still, it seems plausible that variations in slab as well as weak layer properties may lead to crack arrest. For instance, a thinning slab may no longer be able to support crack propagation (Simenhois and Birkeland 2008). The most prominent effect of spatial variations is probably that large variations at the scale of 1 m can prevent failure initiation and certainly crack propagation.

6. CONCLUSIONS

Our understanding of dry-snow slab avalanche release has improved over the last decade by consistently considering avalanche release as a fracture mechanical problem.

In recent years, the fracture mechanical approach has gained more widespread recognition in particular due to (1) the arrival of a new fracture mechanical field test, the propagation saw test (PST), (2) the formulation of a new avalanche release model, the anticrack model, (3) the application of a new analysis method, particle tracking velocimetry, to study fractures in snow, and (4) new developments in numerical modeling enabling more realistic simulations of fracture processes in snow. The anticrack model considered the finite thickness of the weak layer under mixed mode loading and its collapse during crack propagation, and allows the quantitative analysis of PSTs. It triggered an intense and important debate on the role of weak layer collapse and the effect of slope angle on avalanche release. However, collapse should not be misconstrued as a failure mode, as it merely occurs as a response to weak layer failure. Furthermore, there is strong evidence that failure initiation as well as crack propagation propensity are higher in steep than in flat terrain. Finally, the interest in the tensile strength of snow has recently seen a revival as it may determine how far cracks propagate.

Avalanche release can conceptually be described as a sequence of fracture processes including (i) failure initiation in a weak layer underlying a cohesive snow slab, (ii) the onset of crack propagation, (iii) dynamic crack propagation through the weak layer across the slope, and (iv) tensile failure through the slab – equivalent to crack arrest, followed by sliding of the slab.

This conceptual model applies for natural release as well as artificial triggering. The main difference is that failure initiation in the case of natural release follows from a slow damage process where-

as in artificial triggering the rapid localized loading causes the initial crack. Nevertheless, in both cases, failure initiation is more likely to occur where the snow cover is locally weaker than average. However, for artificial triggering these weak spots are not areas where the damage process is concurrently going on – but typically areas where the weak layer has lower strength or the slab is thinner. Thus, spatial variability provides nucleation points for failure initiation, but changes in snow properties may also prevent initiation, and in particular crack propagation.

The stronger focus on fracture mechanics has also led to some changes in snow instability evaluation. Today, we commonly assess how the properties of the slab and the weak layer, in particular the combination of both, affect failure initiation and crack propagation. In other words, when evaluating snow instability, it is always a good idea to ask whether a failure can be initiated and if so if the slab will support crack propagation. As van Herwijnen and Jamieson (2007) pointed out, the propensity for failure initiation can be quite different from the propensity for crack propagation. Skier triggering might not be very likely below a thick and hard slab. However, if a large enough initial crack is formed, crack propagation will certainly be supported by this type of slab. Also, when assessing snow cover stratigraphy and performing snow instability tests, it is best to ask what this information means in terms of layering and fracture mechanical processes: is there a slab, is there a weak layer, can a failure be initiated and will a crack propagate? Obviously not all snow-pack tests answer all these questions (Schweizer and Jamieson 2010) and snow instability evaluation remains a complex task.

There are still many open questions, and there is presently no slab avalanche release model that adequately includes all aspects of the fracture processes and accounts for the multiscale spatial variability. Hence, avalanche researchers still have plenty of work and avalanche forecasting will remain challenging as the single event cannot be predicted.

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