SNOW STABILIZATION FOLLOWING STORMS: FIELD EXPERIMENTS AND MODELLING OF TEMPORAL CHANGES IN SNOW MECHANICAL PROPERTIES FOLLOWING LOADING

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ABSTRACT: Most dry slab avalanches occur during or immediately following loading by snowfall or wind deposition. In the absence of further loading avalanche activity decreases over time. This suggests that avalanche release is facilitated by changes in snowpack properties during loading, and that changes following loading generally help to stabilize the snowpack. This study quantifies these longer term stabilizing changes following loading. We developed a field method to rapidly increase the load on existing weak layers, and used the technique to add 10 cm of disaggregated snow on over 30 isolated columns. We then conducted Propagation Saw Tests (PSTs) in the minutes, hours and days following loading and isolation, with tests ranging from 15 minutes to 4 days. We filmed each test at 120 fps for particle tracking velocimetry analysis, and we utilized a finite element (FE) model to simulate the experiments and better interpret our results. We found that critical crack lengths increased rapidly at first and then more slowly over time. FE simulations of the experiments suggest that changes in critical crack length over time are caused by an increase in slab elastic modulus in the first hours following loading, and then caused by both increasing slab elastic modulus and weak layer specific fracture energy in days following loading. Our results help to illustrate changes in critical crack lengths in the days following loading, and are consistent with field observations of increasing avalanche activity immediately following loading events and decreasing avalanche activity afterwards.

KEYWORDS: avalanche, fracture, loading, slab, particle tracking velocimetry, Propagation Saw Test

1. INTRODUCTION

The first avalanche observers undoubtedly realized that increases in load, i.e. the mass of snow supported by a buried weak layer, typically increases avalanche likelihood over short time scales. Written sources as early as Seligman (1936) and Bader et al. (1939) recognized loading as critically important for avalanche formation, and half of Atwater and Koziol's (1952) original ten contributory factors for avalanche formation were related to loading. Since avalanche release is facilitated by ongoing or recent loading, it follows that loading must favorably change snow cover properties for failure initiation and/or crack propagation, key processes for avalanche release (e.g. Schweizer et al., 2003; van Herwijnen and Jamieson, 2007). However, after loading the snowpack typically stabilizes, so temporal changes in the absence of loading must change snowpack properties to make failure initiation and/or crack propagation less likely.

Thus far no field work has explicitly investigated temporal changes in the mechanical properties of snow related to crack propagation in the hours and days following loading, though Schweizer et al. (2016) looked at temporal changes at weekly intervals. The purpose of this research is to use field experiments to study changes in critical crack length following loading, and to use a modelling approach to study the driving processes behind our field observations. We developed a simple field technique to change slab properties by rapidly loading the snowpack, and then conducted Propagation Saw Tests (PSTs) to investigate changes in the mechanical properties. Our research addresses the following question:

> Once a snowpack is loaded, how do the snow mechanical properties change in the minutes, hours, and days following loading?

This extended abstract is a brief summary of a much more thorough examination of this topic by Birkeland et al. (submitted) and we refer the interested reader to that paper for many additional details.

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2. FIELD AREA AND METHODS

2.1 Field area

We conducted our fieldwork in southwestern Montana at Bacon Rind Creek (44°58'13"N, 111°5'50"W), a site utilized for prior work by Birkeland et al. (2014) and Birkeland and van Herwijnen (2016). This is an open, wind-protected, easterly-facing meadow at 2700 m.

2.2 Field data collection

To investigate how mechanical properties change following a loading event, we conducted tests on four days over a five day period in January 2017. The upper layers of the snowpack consisted of 14 cm of soft (Fist hardness), low density (averaging 135 kg/m^3), new snow (consisting of stellars (PPsd in Fierz et al. (2009)), decomposing stellars (DFdc), and some small near-surface facets (FCsf)) overlying a layer of 5 mm surface hoar. On top of this natural slab we added 10 cm of disaggregated snow using a cardboard frame as described in Birkeland and van Herwijnen (2016). We allowed the snow to sinter for about 5 minutes before carefully cutting around the cardboard with a snow saw and then gently removing the frame. We then isolated the column for our PST completely by cutting around all four sides to well below the surface hoar weak layer with a snow saw, noting the block location and time of isolation in our field book. We left 10 to 15 cm of snow around all our columns until actually doing the PSTs to minimize the effects of temperature and radiation on our isolated blocks.

We conducted a total of 33 PSTs with the time between the isolation of the column and cutting the weak layer ranging from 15 minutes to four days. All tests propagated to END except for the 15 minute test which resulted in a slab fracture (SF) due to insufficient sintering of the added slab. We did remove one test that our video showed was incorrectly cut outside the weak layer, resulting in an anomalously long critical crack length. Thus, for our analyses we had a total of n = 32 tests. We also conducted tests without adding load at the beginning and end of our sampling, both of which resulted in slab fractures. We filmed all tests for particle tracking velocimetry (PTV) analysis (see section 2.3).

After completing a PST we used a metal tube (3.8 cm in diameter and 9.2 cm long) to measure the density of the added slab (in three places along the column) and the density of the snow between the surface hoar weak layer and the added slab (in one place). The metal tube was effective for density measurements of the well-sintered added slab, which exceeded Pencil hardness by the end of the sampling period.

We collected a manual profile of the upper snowpack layers on the first and last day of our sampling period following the methods outlined in Greene et al. (2016).

2.3 Particle tracking velocimetry

We utilized a particle tracking velocimetry (PTV) algorithm (Crocker and Grier, 1996) to determine the displacement of markers inserted in the snow slab above the weak layer to derive several mechanical parameters, namely the critical crack length (r_c), the elastic modulus of the slab (E) and the weak layer specific fracture energy (w_f) (van Herwijnen et al. (2016)). Additional details are included in Birkeland et al. (submitted).

2.4 Finite element simulations of PSTs

We used a modeling approach to investigate the mechanisms leading to observed changes in critical cut length. To assess the propensity of the slab/weak layer configuration to support spontaneous crack propagation, we calculated the critical crack length following techniques developed by Reuter et al. (2015) and Reuter and Schweizer (2018). A key element in our simulations is that slab stiffening and weak layer strengthening are modeled. Additional details about the model and the various inputs we used are included in Birkeland et al. (submitted).

3. RESULTS

We collected our data on a gentle (14° slope angle), southeast-facing slope on four days during a five day period in January, 2017. We loaded the existing snowpack (described in Section 2.2) with 10 cm of disaggregated snow, isolated the 32 columns, and conducted PSTs. The elapsed time between isolating the column and testing it ranged from 15 minutes to more than 5600 minutes (approximately four days). Critical crack lengths ranged from 4.5 to 25.8 cm in our different tests.

The measured density of our added snow ranged from 313 to 397 kg-m^{-3}, with an average of 354 kg-m^{-3}. Consequently, the average additional load from our slab was 0.35 kPa. The added slab quickly hardened, with a hand hardness of P- after only 30 minutes, P after about 90 minutes, and P+ or harder after 24 hours. Thus, the snow we ultimately tested was 10 cm of hard (generally P hardness), dense (generally 350 kg-m^{-3}) snow

over about 14 cm of soft (F hardness), low density (around 150 kg-m^{-3}) snow on top of a layer of 5 mm surface hoar, an optimal configuration for crack propagation (e.g. Schweizer et al., 2011).

Our model performed well for investigating temporal changes following loading, with simulated critical crack lengths matching our measured values ($R^2 = 0.93$, $p < 0.01$) (Figure 1). Interestingly, the model could only adequately simulate changes in critical crack length if we took into account changes in both weak layer specific fracture energy and slab elastic modulus. If we only considered increases in slab modulus (i.e., assuming a constant fracture energy), the model underestimated critical cut lengths with an increasing disparity between our field data and the modelled values at higher cut lengths (results marked as "S" in Figure 1). Further, if we only considered weak layer strengthening the modelled critical cut length values were systematically overestimated (results marked as "W" in Figure 1).

Both measured and modeled critical crack lengths increased following loading (Figure 2). The increase was rapid in the first few hours following loading and then it dropped off to a more gradual increase in the following days (Figure 2a). The
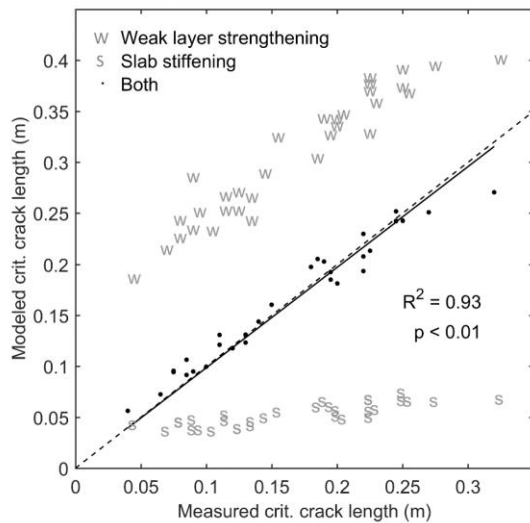

Figure 1: Comparison of measured and modeled critical crack length for our experiments. Our model took into account both slab stiffening and weak layer strengthening (dots). Model results only taking slab stiffening into account are represented by "S" and model results only taking into account weak layer strengthening are represented by "W".

model reasonably reproduced some of the spread seen in our measurements during the initial hours following loading (Figure 2b).

Since the temporal change of both weak layer specific fracture energy and slab elastic modulus in our model followed power laws, our modelled values for these parameters increased rapidly in the first hours of loading and then more slowly over the following days (see Birkeland et al. (submitted) for details). These model results differed from trends observed in our PTV measurements. Our PTV results indicated a great deal of variability in weak layer specific fracture energy in the first hours after loading, including both our lowest and our highest values; after that it is unclear if any increasing or decreasing trend exists (Birkeland et al., submitted). The slab elastic modulus increased rapidly in the first few hours; after that rapid rise it is difficult to discern any trends given the uncertainty in our measurements (Birkeland et al., submitted).

4. DISCUSSION

In our experiment we added snow quickly, and the new load sintered into a stiff slab sitting above the existing slab and the underlying weak layer of surface hoar. Over the first several hours critical crack lengths rapidly increased, followed by more gradual changes in the following days (Figure 2). Our PTV measurements suggest little change in weak layer specific fracture energy over the days of our experiment, though considerable uncertainty exists. A consistent weak layer specific fracture energy following loading would be contrary to previous work demonstrating increasing weak layer shear strength following loading (e.g., Conlan and Jamieson (2016)). Our PTV measurements also showed a temporal trend in slab elastic modulus, with a rapid initial increase caused by the sintering of the added slab. Following this initial increase the temporal trend is not clear given the uncertainties involved in our measurements, but our hand hardness measurements showed gradual hardening of the slab as the hand hardness increased to P+.

We used our model to investigate how we expect the different parameters to change. Our model increases both the slab elastic modulus and the weak layer specific fracture energy according to the relationships described in Birkeland et al. (submitted). An increase in the modulus
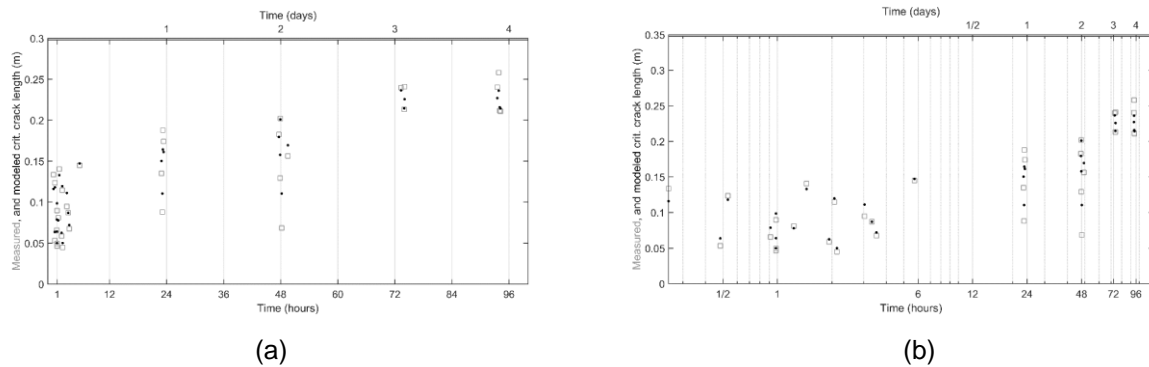
Figure 2: Changes in measured (gray squares) and modelled (black dots) critical crack lengths over time following loading. In (a) we plot time linearly to show the rapid increase in crack length in the initial hours after loading, followed by much slower increases between days one and four. In (b) time is plotted logarithmically to better visualize the data in the early hours of data collection.

makes sense because disaggregated grains – such as the ones we used to add load to our columns – rapidly sinter and strengthen into harder, stiffer layers (Szabo and Schneebeli, 2007; van Herwijnen and Miller, 2013) Likewise, we expect the weak layer specific fracture energy will increase with time following loading since a great deal of research shows that shear strength increases as load increases over time periods from days to months (e.g., Jamieson, 1995; Jamieson and Johnston, 1999; Logan et al., 2007; Conlan and Jamieson, 2016). Finally, in order to effectively simulate the increasing critical crack length over time with the model, we needed to take into account both weak layer strengthening and slab stiffening since leaving out either of these two processes prevented us from making realistic simulations (Figure 1). Thus, our best evidence from the model is that both weak layer specific fracture energy and slab elastic modulus are driving our observed increases in critical crack length after loading.

There are inconsistencies between our PTV measurements and our model results. In general, the PTV results suggest that stiffening is more important than we have modelled and that the strengthening of the weak layer is less important than we have modelled. However, for the model we used the best available literature parameterizations for the two processes. Further, to increase the effect of slab stiffening would require increasing the modulus of the added top layer of the slab to unrealistically high values. Nevertheless, the loading may have affected the modulus of the original slab. We did consider this in the model because we measured the changing density of this layer in the field, but it is possible that there are some other time dependent

behaviors of the original slab that we do not take into account. In the end, our best evidence suggests that both processes are contributing to the changes in critical crack length over time. More clearly understanding how much each of the processes contributes to the observed decreases in critical crack length will require the collection of additional temporal change datasets from the field with detailed measurements of mechanical properties. In addition, lab experiments would also be useful for better understanding some of these changes.

5. CONCLUSIONS

We developed a simple field technique to assess the temporal changes following loading on crack propagation as measured by changes in the critical crack length in PSTs. This technique involved adding disaggregated snow on top of an existing snowpack with a previously buried weak layer. In addition to our field data, we utilized a finite element model to better understand and interpret our results. In short, our results demonstrate: 1) After loading (15 minutes to four days) critical cut length increases in a power law, with a rapid initial increase followed by a more gradual increase, and 2) The initial rapid increase appears to be primarily related to the sintering of the added slab, while the more gradual increase over longer time scales is a combination of slab and weak layer strengthening.

This work represents a field-based parametric study of crack propagation in snow, which is affected by the complex interplay of loading, slab stiffness, weak layer specific fracture energy, and time. Our results confirm previous research (Schweizer et al., 2016; Gaume et al., 2017), and

may be useful for calibrating future efforts to model crack propagation. Indeed, our model reasonably simulated our field results, and might in the future be useful as part of a model chain to predict temporal changes in stability (e.g., Reuter and Bellaire, 2018). For practitioners, our field methods provide a possible technique for safely testing near-surface weaknesses that may not otherwise be fracturing in stability tests. Results might then be roughly extrapolated to areas where the weakness is more deeply buried, such as at higher elevations or in wind loaded areas. In addition, the method may be useful for providing approximate guidance for how an existing snowpack might respond to an anticipated new snow load.

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