THE EFFECT OF INCREASING LOAD ON WEAK LAYER FRACTURE

Karl W. Birkeland[1,*] and Alec van Herwijnen[2]

[1]USDA Forest Service National Avalanche Center, Bozeman, Montana USA
[2]WSL-SLF Swiss Institute for Snow and Avalanche Research, Davos, Switzerland

ABSTRACT: Avalanches failing on buried weak layers tend to be easier to trigger during or immediately following snowfall, suggesting that loading favorably changes snow cover properties for avalanche release. However, previous research showed that thicker, denser slabs (with more load) tend to have longer critical crack lengths in propagation saw tests (PSTs). To address these seemingly contradictory observations, this study quantifies the effect of increasing load on weak layer fracture. In previous research weak layer strengthening may have affected the relationship between load and critical cut lengths. We therefore developed a method to rapidly increase the load on existing weak layers to ensure reasonably constant weak layer strength. On 11 sampling days we used a cardboard frame the size of a PST and added 5, 10, 15, or 20 cm of disaggregated snow on top of PST columns. We allowed the added snow to sinter for 30 to 60 minutes before performing PST experiments and filming each test at 120 fps for particle tracking velocimetry (PTV) analysis. In all cases critical cut lengths dramatically decreased with increasing load (sometimes to almost 10% of unloaded cut lengths), a finding consistent with observations of easier avalanche triggering immediately after loading. Crack propagation speeds also increased with increasing load, consistent with previous work showing higher speeds with increasing slab density. From a practical perspective, this research presents an objective, repeatable, and inexpensive method for testing the effect of loading on surface weaknesses or shallow weak layers. From a scientific perspective, these experiments offer the first controlled, field-based measurements investigating the effect of loading on weak layer fracture, providing results that may be useful for calibrating theoretical models.

KEYWORDS: fracture, loading, slab, Particle Tracking Velocimetry, Propagation Saw Test

1. INTRODUCTION

The first avalanche observers undoubtedly realized that loading increases avalanche likelihood. Written sources as early as Seligman (1936) and Bader et al. (1939) recognized loading as critically important for avalanche formation, and half of Atwater's original 10 contributory factors for avalanche formation are related to loading (Atwater and Koziol, 1952). While true for natural avalanches, practitioners also observe that loading commonly makes avalanche triggering by skiers or explosives easier, unless the weak layer becomes too deeply buried. Since avalanche release is facilitated by recent loading, it follows that loading must somehow favorably change snow cover properties for crack propagation.

In spite of practitioners commonly finding avalanches easier to trigger following loading, Gauthier and Jamieson (2008) showed that thicker, deeper slabs with more load tend to have longer critical cut lengths in Propagation Saw Tests (PSTs). We also observe increasing CT and ECT scores associated with deeper slabs. However, these data have been collected over large spatial and long temporal scales, and thus represent the average conditions of thicker slabs generally being associated with longer cut lengths and increased number of taps rather than how loading might be affecting snow cover properties at shorter time scales.

Schweizer et al. (2016) and Gaume et al. (2016) provide some possible insights into snowpack factors affecting critical cut lengths. Both showed that the critical cut length increases with increasing slab stiffness and increasing weak layer specific fracture energy, and decreases with increasing load. Schweizer et al. (2016) note that the parameter "most strongly influencing the critical cut length seems to be the load" (p. 11). This suggests that Gauthier and Jamieson (2008)'s observations of increasing cut lengths with increasing load may be due to either increasing slab stiffness, increasing weak layer

* *Corresponding author address:*
Karl W. Birkeland, USDA Forest Service National Avalanche Center, P.O. Box 130, Bozeman, MT 59771, tel: 406-587-6954, email: kbirkeland@fs.fed.us

specific fracture energy, or, more likely, both. Consistent with this line of reasoning van Herwijnen et al., (2016; In Press) found that weak layer specific fracture energy increases with increasing overlying stress.

The purpose of this paper is to conduct experiments on the short-term effects of increasing load on crack propagation. We developed a new field technique that changes slab properties by rapidly loading the snowpack. Our technique of rapid loading aims to minimize changes in weak layer specific fracture energy so we can focus primarily on the relationship between loading and critical cut lengths of PSTs. A better understanding of the effect of loading on crack propagation will benefit both scientists and practitioners.

2. FIELD AREA AND METHODS

2.1 Field area

We conducted our fieldwork at two field sites in southwestern Montana. The first is near Bacon Rind Creek (44°58'13"N, 111°5'50"W), a site utilized for prior work by Birkeland et al. (2014). This is an open, wind-protected, easterly-facing meadow at 2700 m. We sampled buried surface hoar weak layers in this area during both the 2014/15 and 2015/16 winters. The second field site is near the summit of Mount Ellis just south of Bozeman (45°34'43.06"N, 110°57'18.60"W). This site is a relatively uniform, mostly wind-protected northeasterly-facing meadow at 2500 m, and we targeted a layer of depth hoar here during the 2015/16 winter. Both sites contain terrain with slope angles from about 20° to 25°, enabling safe access during dangerous avalanche conditions.

2.2 Field data collection

Over two winters we collected data on 11 days at the two field sites. In order to add load to the snowpack in a controlled and consistent manner, we built a cardboard frame 100 cm long, 30 cm wide and 25 cm tall, and we marked the inside walls of this frame at 5 cm increments. We placed this frame on the snowpack and gently and uniformly pressed it 5 cm into the snow by pushing it down to the first line marked on the inside of the frame. At this point we added up to 20 cm of snow load into the frame (Figure 1).

Learning how to add snow to the frame involved some trial-and-error. We first utilized a 2 mm sieve, but sieving snow proved to be too slow for the amount of snow necessary for our tests. The best technique involved cutting blocks out of the lower snowpack, holding them in one hand over the frame, and rubbing them with our other hand to disaggregate the grains which then fell on the snow inside the frame (Figure 2). These layers typically consisted of rounding depth hoar grains. van Herwijnen and Miller (2013) found similar sintering rates for disaggregated depth hoar and

Figure 1: Here we've added slabs of 10, 15, and 20 cm to the snowpack (from right-to-left) and we are preparing the 10 cm slab for a PST. We allowed added snow to sinter for a minimum of 30 minutes.

Figure 2: The most efficient technique for adding load to the snowpack proved to be adding disaggregated grains by hand to a cardboard frame, and then allowing those grains to sinter prior to testing.

rounded grains, with slower rates for disaggregated decomposing fragments. In some cases we stamped with our feet on loose depth hoar to thoroughly disaggregate the grains, and then added the disaggregated grains to our frame with a shovel. In this manner we could quickly add 5, 10, 15 or 20 cm of relatively uniform snow into the frame. We then let this snow sit inside the frame and sinter for more than 5 minutes before gently cutting around the added snow to remove the frame. We allowed the added snow to sinter for at least 30 minutes and sometimes more than an hour before testing (Figure 1). Since disaggregated snow rapidly sinters within the first hours, there were likely some difference in hardness of the added snow due to the somewhat inconsistent sintering times (van Herwijnen and Miller, 2013).

After allowing the added snow time to sinter, we isolated our blocks to perform a Propagation Saw Tests (PSTs) (Greene et al., 2010). We also placed plastic markers in the snowpack and filmed the PSTs with a high speed video camera (120 frames per second at 640 X 480 pixel resolution) for particle tracking velocimetry (PTV) (van Herwijnen et al., 2016). In all cases we cut the ends of the PST normal to the slope to facilitate PTV analysis. After fracture we manually measured the critical cut length, rc, though for our analyses we extracted rc from the videos.

Following the test we measured the load of the snow above the weak layer with a Snowmetrics density tube (5.5 cm in diameter by 30 cm long) in three different places along the fractured block. This method had a few shortcomings. First, occasionally when the weak layer fractured, a secondary fracture would occur below the added slab and the slab would fall off or move. In these cases we tried to measure the added snow as accurately as possible. Second, when we pushed the tube through the added slab snow would sometimes get stuck in the tube and the softer snow below would not get captured in the tube. When this happened we attempted to re-sample in a nearby location.

On some days soft surface snow collapsed while we were adding snow to the snowpack. In these cases, it was difficult to tell if the buried weak layer was affected by the collapse above. To mitigate this we would place the frame, gently compress the snow surface layers with a shovel, and then push the frame down far enough so that the zero line was level with the compressed snow surface.

Finally, we collected a manual snow profile as outlined in Greene et al. (2010).

2.3 <u>Particle tracking velocimetry data analysis</u>

van Herwijnen and Jamieson (2005) pioneered utilizing particle tracking velocimetry (PTV) to investigate fracture in snow. For a review, we refer the reader to van Herwijnen et al. (2016), who summarized and built on the numerous studies using PTV. For this work, we utilize the methods described in van Herwijnen et al. (2016) to derive several mechanical properties relevant for avalanche release, including effective elastic modulus of the slab (E), weak layer specific fracture energy (w_f), and crack propagation speed (c) for each video.

Occasionally the added slab would fracture on the original surface snow immediately following weak layer fracture. This caused snow to fall in front of the markers, and made assessing all of the mechanical properties difficult or impossible. In a few cases the observer was in front of some of the markers during cutting, preventing calculations of E or w_f. In nearly all cases we could measure a value for c, but for several tests we could not obtain values for E or w_f.

3. RESULTS AND DISCUSSION

3.1 Adding load

The method of adding disaggregated snow allowed us to quickly load an existing weakness in the snowpack. Taken together, we see that adding a 5, 10, and 15 cm to the snowpack is the equivalent of about 22, 45, and 67 mm (0.9, 1.7, and 2.6 in) of water equivalent (Figure 3). For these intervals the increase in added load is fairly linear, with about 22 mm of water added for each 5 cm of disaggregated snow. The last 5 cm of disaggregated snow resulted in a little less added load, with an average of 79 mm (3.1 in) of water equivalence in our 20 cm of added snow. This may be because we weren't able to apply that last layer quite as evenly, or it might be due to some of the difficulties we had in making accurate density measurements of the thicker added slabs. Nevertheless, overall our results suggest this technique works well for efficiently adding a fairly consistent load to an existing snowpack for further testing.

Throughout this paper we will refer to the 5, 10, 15, and 20 cm added slabs as our load rather than the actual load added to the snowpack. This approach simplifies our results for practitioners looking to do similar measurements. Further, the essence of our results and conclusions do not change when substituting actual load for the depth of the slab added to the snowpack.

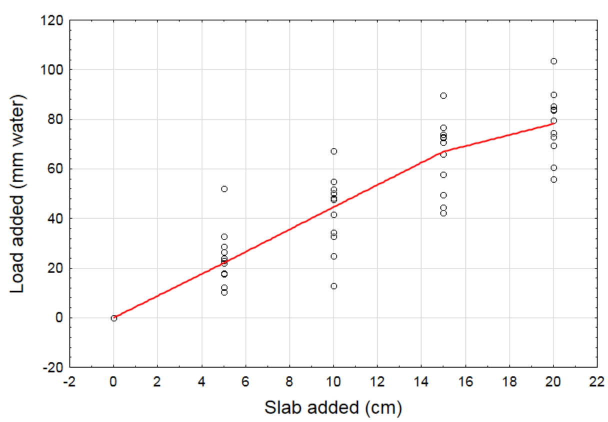


Figure 3: Plot showing the measured snow water added with the various added snow depths for all data on all days. The red line represents the average, so 5 cm of added snow contains about 22 mm water equivalent for the 5, 10, and 15 cm added slabs, with slightly less water added in the last 5 cm of the 20 cm added slab.

3.2 Changes in critical cut length and mechanical properties

As expected, our results demonstrate dramatic decreases in critical cut length with increasing load (Figure 4). On all 11 days r_c decreased with increasing load (Figure 5a), though on some days we did observe outliers where r_c increased for one or two tests (Figure 5b). These outliers are likely caused by experimental errors due to the inaccurate positioning of the saw cut in the PST. We found that even small (< 1 cm) deviations from the weak layer resulted in much greater values of r_c. Further, we note that such positioning errors can only increase cut lengths since incorrect placements cannot possibly decrease the cut lengths.

To assess if the decrease in r_c was due to a decrease in weak layer specific fracture energy or a decrease in elastic modulus, we estimated both these variables with PTV. Looking at all our data shows neither w_f (p = 0.06) nor E (p = 0.83) significantly increase with increasing load (Figure 6), suggesting that the increasing load was primarily responsible for the observed decreases in r_c.

Not surprisingly, we also observed increasing fracture speeds as we increased the load (Figure 7). Since adding load resulted in higher average slab densities, this result is consistent with work by van Herwijnen and Birkeland (2014) showing increasing *c* with higher density slabs. Indeed, the

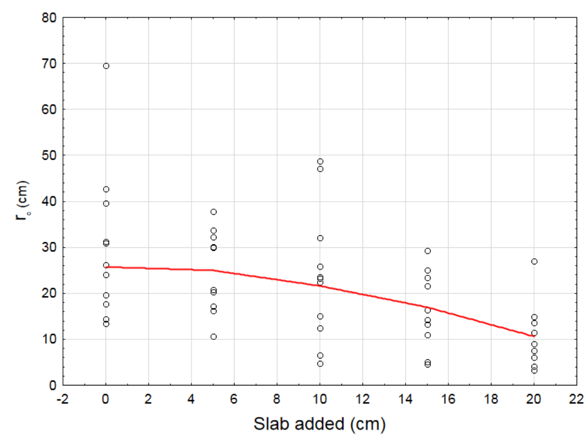
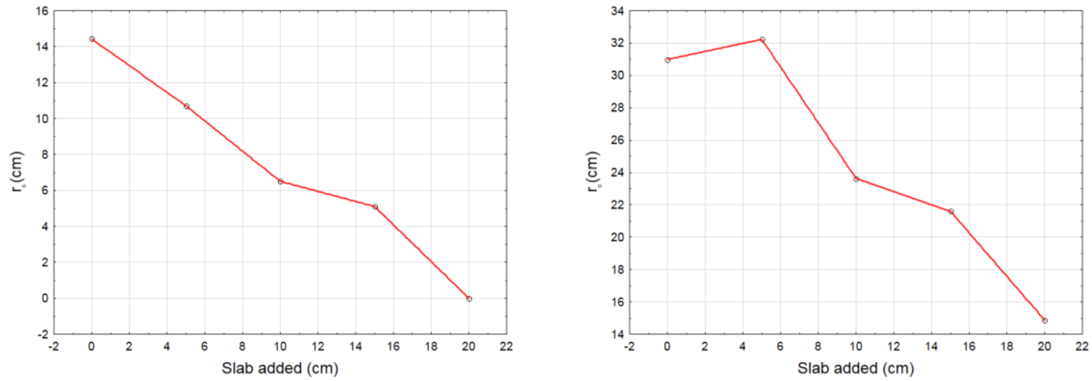
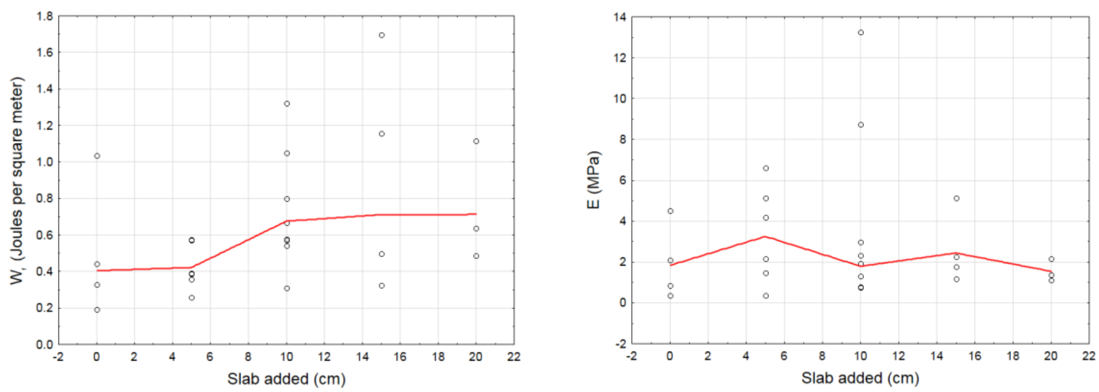


Figure 4: Combining all of the tests on all days shows decreasing cut length (r_c) as the depth of the added slab increases. The red line represents the average value for all 11 field days.



(a) (b)

Figure 5: These two sampling days demonstrate some of the dramatic decreases in cut length (r_c) we observed with increasing load. In (a), the weak layer fractured when the block was isolated after adding a 20 cm slab so r_c was noted as zero. Example (b) shows a case where the cut length increased with the 5 cm added slab, something that we observed occasionally in our data and that we attribute to either spatial changes in the snowpack or – more likely – to our inability to always keep the saw exactly in the weak layer.



(a) (b)

Figure 6: Neither (a) weak layer specific fracture energy ($p = 0.06$) nor (b) slab elastic modulus ($p = 0.83$) increased significantly with increasing load, thereby suggesting that the increasing load was the primary driving factor for the observed decreasing cut lengths. The red line represents the average for each loading interval.

data for this paper show a similar relationship with a highly significant increasing trend ($p < 0.001$). van Herwijnen et al. (2016) show that increased c is associated with longer crack propagation distances.

Taken together, our results quantitatively demonstrate how increasing load affects crack propagation and avalanche triggering. Increased loads decrease critical cut lengths, so smaller initial cracks in the weak layer are required for the onset of rapid crack propagation. Further, propagation speeds increase with additional load. Both of these factors help explain why practitioners observe that new snow loading makes an existing snowpack “touchy”, “sensitive”, and easier to trigger.

4. CONCLUSIONS

We developed a new field technique to better assess the effect of load on crack propagation as

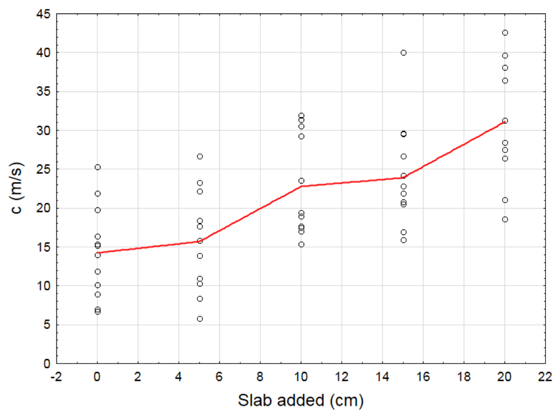


Figure 7: Adding load resulted in faster fracture speeds, sometimes by as much as a factor of five. The red line represents the average for each loading interval.

measured by changes in critical cut length of PSTs. This technique involved adding snow on top of an existing slab to investigate the effect of increasing load on critical cut length. Our results demonstrate that adding load dramatically decreases PST cut lengths and increases crack propagation speeds, helping to explain why avalanche triggering is greatly facilitated by loading.

This work is significant from both practical and scientific perspectives. For practitioners, the method may be useful for providing some rough guidance for how an existing snowpack might respond to an anticipated new snow load. From a scientific perspective, this is the first field-based work to specifically focus on the effect of loading on crack propagation. As the first field-based parametric study of crack propagation, our results show the interplay of loading, slab stiffness, and weak layer specific fracture energy on critical cut lengths. These results confirm previous numerical parametric studies (Gaume et al., 2016; Schweizer et al., 2016), and may be useful for calibrating future efforts to model crack propagation.

As always, many questions remain to be investigated in detail. In particular, the role of time needs further study. In coming field seasons we plan to add load to existing weaknesses and then to observe how slab stiffness, weak layer specific fracture energy, and critical cut lengths change over time. We also plan to more carefully assess the density and hardness of all slab layers. In the end, this work provides a solid baseline for future field work and modelling verification.

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