THE EFFECT OF CHANGING SLAB THICKNESS ON FRACTURE PROPAGATION

Ron Simenhois[1,2,*] and Karl Birkeland[3]

[1]Copper Mountain Ski Area, Copper Mountain, Colorado
[2]Mount Hutt Ski Area, Canterbury, New Zealand
[3]U.S.D.A. Forest Service National Avalanche Center, Bozeman, Montana

ABSTRACT: Many avalanches are triggered from shallower parts of a slope. Past research demonstrates that initiating fractures in such areas is easier than in deeper places where the applied stresses must penetrate through more overlying snow before affecting the weak layer. However, to our knowledge there is no work on whether fractures more effectively propagate from deeper to shallower areas, or from shallower to deeper areas. During the 2006/07 and 2007/08 winters, we looked at fracture propagation using standard Extended Column Tests, modified Extended Column Tests with column widths of 200 and 300 cm, and Propagation Saw Tests. We tested fracture propagation on slopes with highly variable weak layer depth and with reshaped slab thickness. Our results suggest that fractures are more likely to propagate further when traveling from under thin to thick slabs than in the opposite direction. We support our test results with four case studies. In these cases, slopes only partially released with big explosives applied where the weak layer was deeper, but then avalanched entirely a few days later when tested with small loads where the weak layer was shallower. Thus, shallower areas of the slab may be both the easiest place to initiate a fracture and also the best place from which to propagate a fracture. These results have broad implications for backcountry travel, avalanche avoidance, and avalanche control work.

KEYWORDS: ECT, extended column test, PST, propagation saw test, fracture propagation

1. INTRODUCTION

Dry slab avalanches threaten people living in, recreating in, and traveling through alpine environments. Avalanches result from fracturing along a weak layer or interface underlying a stronger slab. Fractures must first be initiated to a specific length in order to achieve the critical energy release rate required for fracture propagation. On an inclined slope, the outward fracture driving energy increases with the propagation of the fracture. Once the slab can no longer sustain the fracture's driving energy, it fails and an avalanche is released (Gauthier, 2007 (p. 169-170)).

Human-triggering of avalanches is important since most avalanche fatalities result when the victim or a member of their party releases the avalanche. People are more likely to initiate fractures in thin snowpack areas because the applied stress on a weak layer in the snowpack decreases with depth (Camponovo and Schweizer 2001). Further, research suggests that the critical length for self-propagation is smaller where the overlying slab is thinner (Bažant et al. 2003), increasing the likelihood of skier triggering in thinner areas. Field observations are largely consistent with these research results. Both professionals and recreationists report that skier and explosive-triggered avalanches are easier to release from thinner areas of the snowpack. The common assumption has been that those observations result from the relative ease of *initiatiating* a fracture in thin areas of the snowpack. However, we still don't know how thinner and thicker areas of the slab affect the *propagation* of fractures.

This research attempts to measure the snowpack's fracture propagation propensity across areas with varying slab thickness. We used the Extended Column Test (ECT) (Simenhois and Birkeland 2006; 2007), modified Extended Column Tests with column width of 200 and 300 cm, and the Propagation Saw Test (PST) (Gauthier and Jamieson 2007; 2008) to assess the propagation propensity of fractures. In this

[*] *Corresponding author: Ron Simenhois, P.O. Box 4888 Silverthorne, CO. USA 80497; tel: (970)-262-3820; email – ron_si@yahoo.com.*

research we look at side-by-side test results in areas with naturally varying slab thickness and in areas where we reshaped the slab to create varying slab thickness (Figures 1 and 2). Our results suggest that fractures are more likely to propagate from under thin to thick slabs than the other direction. We support our data with four case studies where fractures initiated on slopes where the slab above the weak layer was thick and then where it was thin. Since a highly variable slab depth is common in avalanches start zones, this research has practical implications for avalanche mitigation and prevention, traveling in avalanche terrain, where to dig snowpits, and conducting ECT and PST tests in areas with varying slab depths.

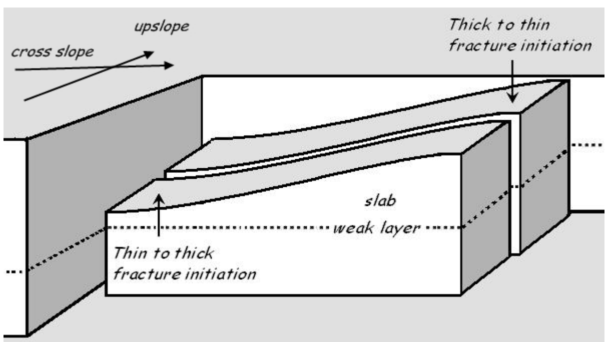

Figure 1: Schematic illustration of side-by-side extended column tests. Fractures are initiated under thin and thick parts of the slab by placing and tapping on a shovel on the thin side in one test and on the thick side in the second test.

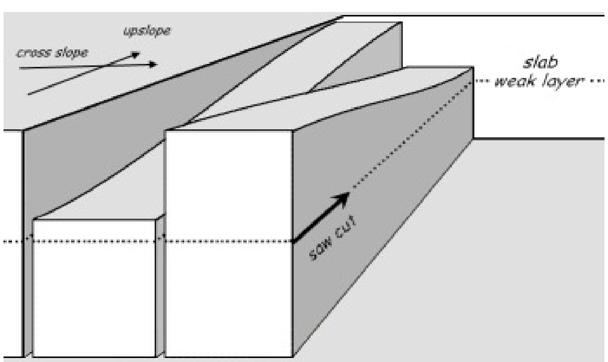

Figure 2: Schematic illustration of side-by-side Propagation Saw Test with varying slab depth.

2. DATA AND METHODS

We conducted our study in and around Copper Mountain, Colorado and Mt Hutt, New Zealand. During the 2006/07 and 2007/08 northern hemisphere winters we collected modified ECT and PST results from 41 pits, while during the 2008 southern hemisphere winter we collected an additional 11 pits. All of our 52 pits were on slopes with high fracture propagation propensity, as evidenced by recent avalanche activity on the same or similar slopes (33 of the 52 pits) or as indicated by fracture propagation results using a standard ECT or PST. In 20 pits the slab thickness above the weak layer changed naturally within a column length (90 cm for the ECT and 100 cm for the PST) and in the other 32 pits where the slab thickness above the weak layer was consistent across the column, we reshaped the slab above the weak layer with a snow saw. We reshaped the slab thickness across a column to the original thickness on one end and the minimum thickness that could withstand the stress of fracture initiation without cracking. Change in slab depth across the column varied from 12 cm to 50 cm, with an average change of 30 cm (Table 1).

Data collected in each pit included results from side-by-side ECTs, modified ECTs with column widths of 200 cm in 15 pits, 300 cm in eight pits and PSTs in 18 pits (Figures 1 and 2). In each set, a fracture was initiated from where the slab was thick in one test and in the other test the fracture was initiated where the slab was thin. We also collected grain size and type, layer hardness, layer thickness and slab density (Greene et al. 2004). In one case the data collected was from a grid. On 4 April 2007 we dug a grid of six by four pits on an east-facing 27° slope at an elevation of 3765 m in Colorado. In 17 of those pits we shaped the slab to be thinner toward one end of the column on a 90 cm ECT column.

3. RESULTS

In our dataset (consisting of 116 side-by-side tests from 52 pits) fractures that initiated under the thin part of the slab always propagated along the weak layer or interface across the entire column toward the thicker part of the slab. However,

Table 1: Summary of slab parameters comparing naturally varying slabs and manually shaped slabs.

	Manually shaped slabs	Naturally varying slabs	All observations
Number of pits	32	20	52
Number of pairs of ECTs	32	17	49
Number of pairs of PSTs	13	5	18
Minimum slab thickness (cm)	1	8	1
Average minimum slab thickness (cm)	8	21	13
Maximum slab thickness (cm)	63	58	63
Average maximum slab thickness (cm)	43	46	44
Maximum slab variation (cm)	50	42	50
Minimum slab variation (cm)	16	12	12
Average slab variation (cm)	34	24	30

when we initiated the fracture under the thick slab in the same pits it consistently failed to propagate across the entire column toward the thinner slab. In all cases where the fracture did not propagate fully, the slab cracked before the fracture along the shear plane reached the end of the column.

In 32 of 53 pits we manually shaped the slab above the weak layer. In these pits we conducted 17 sets of side-by-side ECT in 17 different pits, six sets of modified ECT with a 200 cm column in six different pits, and 13 side-by-side PST tests in 13 different pits. No matter what test we used, our results were consistently the same. Fractures propagated across the entire column from under a thin slab to under a thick slab, but would not propagate across the entire column in the other direction. Some of our data are from one array of 17 pits on a 27° east facing slope from 4 April 2007. This slope had a P hard slab with density of 390 kg/m^3 sitting on top of 0.5mm, 4F+ hard layer of buried near surface-faceted-crystals. In all of those pits fractures propagated across the entire column only in one direction, from where the weak layer was shallow to where it was deep.

In order to ascertain whether or not our results might be due to our manual manipulation of the slab, we also investigated areas where the slab depth varied naturally across the column. Of our 52 pits, 20 had such natural slab thickness variations. Like the cases where we modified the slab, in all of those tests (17 sets of two side-by-side ECTs or modified ECTs and one set of five side-by-side PSTs), fractures propagated across the column from the thinner to the thicker slab, but did not propagate from the thicker slab back towards where the slab was thinner.

4. CASE STUDIES

Our test results are supported by four case studies from the 2007/2008 northern hemisphere winter around Copper Mountain, Colorado. In all cases fractures initiated in areas where the weak layer was under a thicker slab, but did not fully propagate across the slopes. However, those same slopes slid in their entirety a day or two later when tested with much smaller loads on areas where the slab above the weak layer was thinner.

Case study 1. The first case was on 1 January 2008 on a 37° east facing slope at an elevation of 3680 m. On 31 December 2007 this slope was tested with both one and two kg charges on the upper part of the slope where the weak layer depth was about one meter. Those explosives produced cracks down to the weak layer and about four meters along it. However, the majority of the slope remained intact. On 1 January 2008 this slope avalanched with a one kg charge placed in the compression zone where the weak layer depth was about 30 cm. There was no additional load on this slope between the time it was initially tested and the time it slid, and the perimeter of this slide included the two explosive placements from the day before (Figure 3).

Case study 2. The second incident occurred on 4 January 2008 on a 35° northeast facing slope, at an elevation of 3800 m. This slope was tested numerous times on January 2nd and 3rd with no results. On 2 January a 14 kg charge was placed in area where the slab above the weak layer was a meter to a meter and a half thick. On 3 January an eight kg charge was placed where the slab was one meter thick. On 4 January a patroller triggered a hard slab avalanche (HS-Ab-D4/R5-O) by snowboarding across the lower part of the same slope where the slab was less than 10cm thick. Explosive work from the previous two days was visible on the bed surface with two dents of seven and 10 m in diameter (Figure 4), demonstrating that the applied charges were effective in initiating the fracture. However, those fractures did not propagate sufficiently to result in an avalanche. There was no additional load added to the slope between January 2nd and 4th.

Case study 3. The third case study occurred on 23 January 2008. On 21 January ski patrollers triggered a hard slab avalanche on a southeast facing, 38° slope at an elevation of 3750 m with 2.7 kg of explosive. This avalanche was 10 m wide and 50 – 80 cm deep. Returning on 23 January, ski patrollers triggered another avalanche with 0.9 kg of explosive from an area where the weak layer was about 20 cm deep. This slide was 25 m wide and contained the slide from the day before within its perimeter.

Figure 3: Case study from 1 January 2008, in this photo the disturbance in the bed surface is from the explosive work on the day before this slope avalanched.

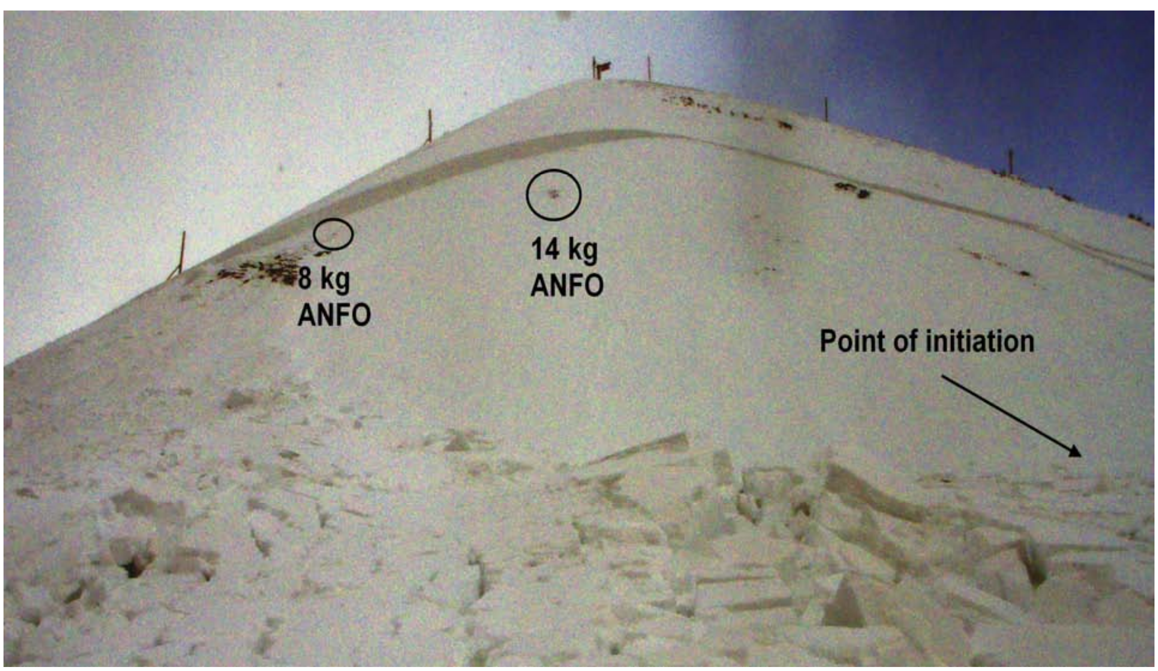

Figure 4: Case study from January 4, 2008 locations where explosives were placed and left marks on the bed surface.

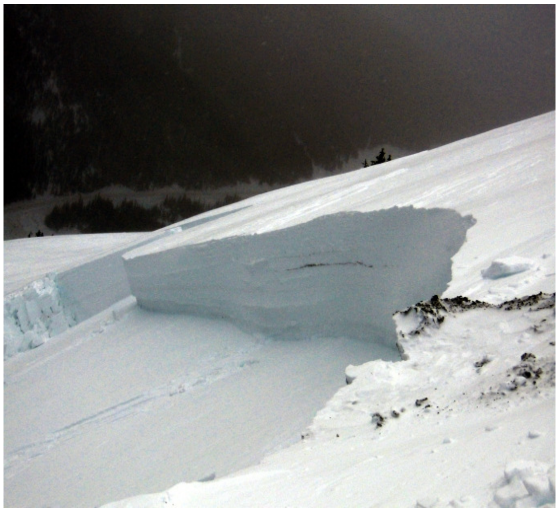

Figure 5: Case study from 8 February 2008, bomb crater from explosive work two days before the slope failed is visible on the right side of the picture.

Case study 4. The fourth case occurred on 8 February 2008. On 6 February ski patrollers placed 10 kg of explosives on a 37°, east-facing slope at an elevation of 3880 m. Weak layer depth at the location of explosive placement was about 80 cm. The explosive charge produced only cracking around the crater down to the weak layer. Two days later the slope released when a one kg charge was placed at the compression zone where the weak layer depth was about 20 cm. The crown face of this soft slab avalanche was where the 10 kg charge was placed two days earlier (Figure 5).

5. DISCUSSION AND CONCLUSIONS:

Both theory and practice support the idea that fractures are more likely to be initiated in thinner areas of the snowpack. However, our limited data and field observations show that fractures are also more likely to *propagate* from areas with thinner slabs toward areas where the slab above the weak layer is thick, than in the other direction. Hence, our results suggest that these two mechanisms reinforce each other, increasing the potential for triggering avalanches in thinner areas. Further, our case studies suggest that even when explosives large enough to initiate fractures are placed in deep areas of the slab, in some cases they might not trigger avalanches, while smaller loads placed in thinner areas may release the entire slope.

Our fracture propagation test dataset does not contain cases where, in the same pit, a fracture propagated from under thick slab toward a thinner slab and did not propagate in the other direction. However, it would be wrong to assume that fractures initiating under thicker slabs will not propagate toward areas of thinner slabs. We and many others have observed fractures propagating from thicker slab areas toward thinner slab areas under some conditions. Further, it is also possible that under some conditions that we haven't observed yet, fractures in our propagation tests may come to an arrest when propagating from thin to thick areas.

5.1. Practical implications

Our findings of asymmetric fracture propagation propensity over slopes with spatially variable slab thickness have practical implications on a variety of subjects.

1. **Avalanche mitigation:** Explosive placement is likely be most effective when placed in area where the slab is thinner than at its thickest spot. Still, to support fracture propagation on the weak layer, a slab needs to be strong enough and therefore thick enough to withstand the energy transfer at the point of initiation (Gauthier, 2007).
2. **Avalanche prevention:** Structures for snowpack anchoring may be more effective if their design takes into account the prevailing winds and creates highly variable slab thickness across start zones. Highly variable slab thickness across start zones may help to minimize avalanche size.
3. **Escape route:** When planning an escape route in case of slab release, aiming to an area of thin slab will increase the chance of getting off the slide perimeter and into areas where the propagating fracture is less likely to reach. This strategy also puts you in

areas with a smaller volume of moving snow.

4. **Snowpit location:** Slab thickness above weak layers influences stability tests. When digging snowpits in areas of variable slab thickness, fractures in ECT and PST should be initiated where the slab is thinner since such tests are less likely to produce false-stable results. Further, care should be taken in snowpits where the slab is too thin. Some of these tests may indicate lower fracture propagation propensity than in areas of the slope with a thicker slab. Hence, if propagation tests results are inconsistent with other stability tests and shear quality/fracture type, another test should be done in area of the slope where the overlying slab is thicker.

Acknowledgments

The American Avalanche Association provided partial support for this work through a practitioners grant to R. Simenhois. This work has benefited from discussions with Ed Adams and Ladean McKittrick, and Ed also reviewed this paper for us. Many thanks to the Copper Mountain and Mount Hutt Ski Patrols for their support of this work.

References

Bazant, ZP G Zi, D McClung, 2003. Size effect law and fracture mechanics of the triggering of dry snow slab avalanches. Journal of Geophysical Research, 2003

Gauthier, D. and B. Jamieson. 2007. The propagation saw test. Avalanche.ca - The Journal of the Canadian Avalanche Community 83(winter 07-08), 60-63.

Gauthier, D.M., 2007. A practical field test for fracture propagation and arrest in weak snowpack layers in relation to slab avalanche release. PhD thesis, Dept. of Civil Engineering, University of Calgary, Calgary, Canada.

Greene, E.M. et al., 2004. Snow, Weather and Avalanches: Observational guidelines for avalanche programs in the United States. American Avalanche Association, Pagosa Springs, Colorado, 136 pp.

Schweizer, J. and Camponovo, C., 2001. The skier's zone of influence in triggering of slab avalanches. Ann. Glaciol., 32: 314-320.