FRACTURE SPEEDS OF TRIGGERED AVALANCHES

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ABSTRACT: Observations by practitioners suggest that fracture speeds are often much faster than recently reported measurements. These measurements include speeds along isolated beams ranging from 15 to 45 m/s, as well as the speed of a meadow collapse of 20 m/s. Since reported velocities appear to be slower than many observed avalanches, we analyzed a sample of 27 videos to estimate avalanche fracture speeds. Time was measured by counting video frames from the explosive trigger to visible slab fractures, and distances by on-site measurements, picture scaling, and Google Earth. Though our speeds vary widely (from 18 to 428 m/s), most of our values fall in the range of 50 to 125 m/s, which clearly exceeds previously reported values. We also investigated the relationship between fracture speed and other characteristics, such as explosive size. Interestingly, in videos with visible crowns and stauchwalls, the stauchwall opens first or at the same time 33% of the time. Our results may improve our understanding of avalanche release, as well as providing practical guidance for explosive placements.

Key words: Avalanche, video, fracture speed

1. INTRODUCTION

As a young Alta patroller, the lead author triggered an enormous avalanche on skis from flat terrain. He was amazed how quickly the resulting propagation "collapse wave" put the entire mountainside in motion above him. His observations over a 40-year career led him to believe that fracture speeds are often much faster than recent measurements on isolated beams, and this formed the motivation for this paper. A better quantification of fracture speeds on actual avalanches may help improve our understanding of avalanche release.

For the most part, previous research measured fracture speeds over relatively small areas or isolated beams rather than at the scale of actual avalanches. Johnson and others (2004) measured the speed of a collapse in a flat meadow using geophones, coming up with 20 +/- 2 m/s over a distance of about 8 meters. van Herwijnen and Jamieson (2005) reported similar speeds on isolated beams, with values ranging between 17 and 26 m/s. van Herwijnen and Birkeland (2014) also measured speeds on isolated beams and found values from less than 10 m/s to more than 40 m/s, with increasing speeds correlated to increasing slab density. Extended Column Tests (Simenhois and Birkeland, 2009) were conducted and compared with Propagation Saw Tests (Gauthier and Jamieson, 2008). Similar fracture speeds between the two tests suggest that fracture speeds are independent of triggering mechanism. Interestingly, their data demonstrate increasing fracture speeds as mean slab density increases.

Fracture speed measurements of actual avalanches are rare. van Herwijnen and Schweizer (2011) recently measured a fracture speed of 42 +/- 4 m/s for an avalanche in Switzerland using a seismic sensor array. Rougher measures of fracture speed can be estimated from videos of avalanches. Using 11 videos, van Herwijnen (2005) calculated fracture speeds ranging from about 15 to 32 m/s. In this paper, we utilize similar methods on a broader range of videos to estimate fracture speeds. Our calculated speeds are substantially higher than previously reported values, ranging from less than 20 m/s to over 400 m/s with most values in the range from 50 to 125 m/s. Velocities above 190 m/s are documented only from secondary fractures developing after the initial release.

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2. METHODS

2.1 Analysis methodology

Frame by frame analysis was conducted on a sample of 27 videos from a wide variety of sources including the Milford Road in New Zealand, Kootenay Pass in Canada, Gaz-Ex footage from Switzerland, and the Chugach and Coast Ranges in Alaska, as well as a variety of other locations. All videos analyzed were artificially released avalanches so the initial time of fracture initiation could be easily determined. Other videos available from skier, rider, and snowmachine-triggered events were not used because the exact instant of release cannot be accurately determined. Analysis by the frame allows us to determine the initiation time within a single video frame of time accuracy, but evidence of initial fracturing is not quite as accurate in some cases. In reality there is a lag time between a weak layer fracture reaching avalanche boundaries and the time the boundary fracture appears in a video frame. This lag time would result in our estimates being minimum fracture speed estimates. Measurement error is provided as an average of the samples.

2.2 Measurement error calculations:

Time measurement increments are one video frame primarily at 25 frames per second (fps) or 30 fps. Thus, the maximum time measurement error is one video frame when a fracture was initiated and one to two frames when a crack in the slab first appeared. We estimated our distance measurements error to be ten meters for Google Earth measurements and one meter for field measurements with laser range finder. The largest potential error in timing is thus calculated as -.06 seconds to + .12 seconds. Smaller events could have a significant distance error using Google Earth measurements but an event of over 100 meters will only have a 10% error. As an example of the combined effects, an event of 100 meters in length with a speed of 100 m/s could have an error range at a maximum of 78 m/s(combined effects of 10 meter distance error short plus .12 seconds short), to 122 m/s. In reality, a sample of this size tends to cancel out these errors substantially through over and under averaging.

3. RESULTS AND DISCUSSION

3.1 Fracture Speed Measurements

Our speed measurements varied between 18.9 ±1 m/s and 427.9 ±82 m/s. The average speed was calculated at 80.3 m/s (Tbl.1). Fracture travel distances were between 12 meters and 590 meters from the point of initiation with an average distance of 126 meters. The time it took fractures to reach the avalanche's boundary varied between 0.25 and 8.73 seconds.

Table 1- Fracture Speeds

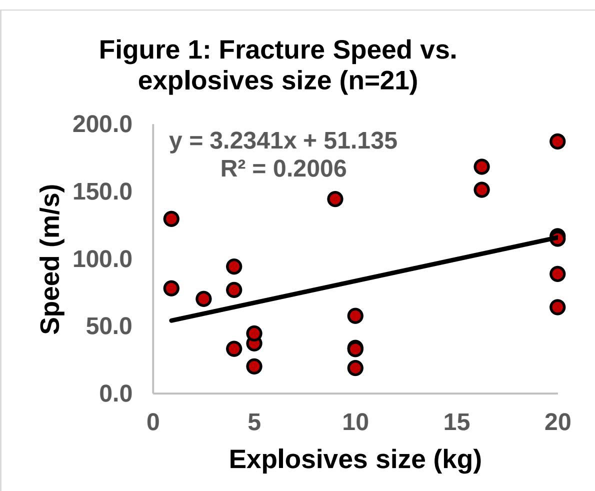
Site	Time to fracture	Distance meters	Speed M/s	Failure Point
Milford #1	1.080	202	187.0	Stauchwall
Milford #2	1.440	92	63.9	Stauchwall
Milford #3	1.960	174	88.8	Stauchwall
Milford #4	0.960	112	116.7	Mid slope
Milford #5	1.080	124	114.8	Stauchwall
Milford #6	6.000	590	114.8	Unknown
MP 43	1.040	98	94.2	Same time
Kern	1.480	104	70.3	Stauchwall
Kootenay #1	1.033	35	33.9	Crown
Kootenay #2	1.033	34	32.9	Crown
Kootenay #3	3.000	173	57.7	Crown
Kootenay #4	8.726	165	18.9	Crown
Gaz-Ex #1	0.786	70	89.1	Unknown
Gaz-Ex #2	0.786	50	63.6	Unknown
Wyoming Bow	2.160	280	129.6	Crown
Tucker Mt.	3.566	278	78.0	Crown
Tucker Mt.	0.701	118	168.4	Stauchwall
Tucker Mt.	0.966	146	151.2	Stauchwall
Kensington	0.250	36	144.2	Stauchwall
Kensington	0.417	32	76.8	Crown
Kensington	0.430	16	37.2	Crown
Kensington	0.458	20	44.5	Same time
Kensington	0.403	13	33.0	Same time
Kensington	1.699	34	20.0	Crown
BNSF Rail	0.367	12	33.0	Crown
BNSF Rail	0.333	19	56.0	Stauchwall
BNSF Rail	0.433	22	49.7	Crown
			80.3	**Average**

In many cases the initial fracture was at or near the maximum extent of fracture travel. In some cases secondary fractures developed at some distance from the initial fracture. The highest speeds recorded were fractures that developed in a downslope mode within secondary releases including one instance of propagation velocity far in excess of other events (Kootenay #2). Velocity averages in the secondary fracture results are heavily skewed by the single high-speed propagation that occurred in the samples so speeds are also calculated throwing out the high value (Tbl.2)

Table 2- Secondary FX Speeds			
Site	**Time to second fracture**	**2nd distance meters**	**2nd speed M/S**
Milford #1	1.600	287	179.4
Milford #2	2.280	162	71.1
Milford #5	1.600	257	160.6
MP 43	3.400	335	98.5
Kern	2.880	284	98.6
Kootenay #1	1.466	62	42.3
Kootenay #2	0.266	114	427.9
Wyoming Bowl	1.680	125	74.4
Tucker Mt.	0.701	32	45.7
Kensington	0.291	29	99.6
		Avg.	**129.8**
Average without Kootenay #2			**96.68**

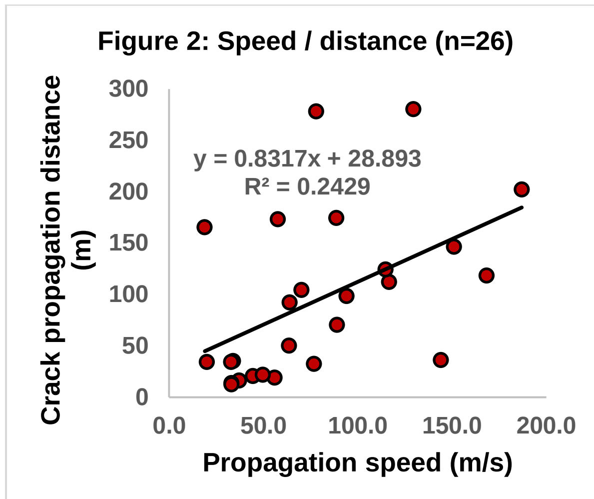
3.2 Trigger size vs. fracture velocity

We compared fracture velocity to trigger size where the explosives' size trigger was known. Our data show a very weak correlation between trigger size and weak layer fracture speed (R^2 = 0.21, p-value: 0.04), (Fig. 1). This data is in line with previous research suggesting that weak layer fracture speed is independent of initiation speed (van Herwijnen and Birkeland, 2014).



3.3 Fracture Speed vs. propagation distance

Visually, it appears that our data demonstrates a slight increase of propagation distance with an increase in propagation speed. During our analysis, we elected to remove two outlier values due to their excessive leverage on the relationship and because we calculated these values slightly differently from the others. The first had a high speed for a short distance and the second had a low speed for a long distance. If these two values are removed, the remaining data show a rough increase of distance with speed. Statistical tests demonstrate that while the relationship is highly significant (p = 0.01), it still only explains about 24% of the observed variance (R^2 = 0.241) (Fig. 2). Our results suggest that although propagation speed may have some influence on crack propagation distance, terrain and snowpack are likely more dominant influences on propagation distance.



3.4 Fracture Location

Frame by frame analysis reveals that a substantial number of events (33%) release initially at the stauchwall then is followed shortly afterwards by fractures appearing at the crown. In the majority of events that have their initial fracture at the stauchwall, the explosive charge is much closer to the crown location than the stauchwall. Anecdotal evidence suggests that events where the stauchwall is the first visible slab boundary may have deeper fracture depths. We have developed two groups of velocity data for those where the stauchwall is first visible versus the rest of the sample. There is a substantial difference in the propagation velocity (p = 0.002) of these two groups with the average of the stauchwall group at 116 m/s versus 62 m/s for the other group (Tbl.3).

Our results provide further evidence that higher density slabs may support faster propagation velocities as has been previously suggested for isolated beams (van Herwijnen and Birkeland, 2014). Our stauchwall group consisted of generally deeper slabs, which we would expect to have a higher density than the relatively thinner slabs in our non-stauchwall group.

Table 3 - Speed of stauchwall failures

Site	1st speed M/S	Failure Point
Milford #6	115	Unknown
Kootenay #1	34	Crown
Kootenay #2	33	Crown
Kootenay #3	57	Crown
Kootenay #4	19	Crown
Tucker Mt.	78	Crown
Kensington	77	Crown
Kensington	37	Crown
Kensington	20	Crown
BNSF Rail	33	Crown
BNSF Rail	50	Crown
Milford #4	117	Mid slope
MP 43	94	Same
Gaz-Ex #1	89	Unknown
Gaz-Ex #2	64	Unknown
Wyoming Bowl	130	Unknown
Kensington	45	Unknown
Kensington	33	Unknown
Average	**62**	
Milford #3	89	Stauch wall
Milford #5	115	Stauch wall
Tucker Mt.	168	Stauchwall
Tucker Mt.	151	Stauchwall
Kensington	144	Stauchwall
BNSF Rail	56	Stauchwall
Milford #1	187	Stauchwall
Milford #2	64	Stauchwall
Kern	70	Stauchwall
Average	**116**	

3.5 *Fracture speed vs. depth*

Although we can imply relatively deeper or shallower slabs, exact fracture depths for the analyzed events are not known. Visual evidence based on the height of the explosives powder cloud suggests that deeper fractures tend to have faster fracture speeds but our data are not sufficient to rigorously support this conclusion.

3.6 *Fracture speeds driven by explosives*

Previous work into the attenuation of explosives energy in snow has shown the effectiveness of dampening and rapid attenuation for this medium. While it's possible that fractures in our data set are initially driven by explosives energy in the immediate vicinity of the charge, the effects of this would rapidly dissipate (pers. com. Miller 2014). As a cross check, several skier and sledder triggered avalanches were reviewed. Exact determination of the trigger time is not possible in these videos, but in some cases fracture initiated near the skier or sledder and then propagated downslope and laterally for a considerable distance. In both cases where this evidence was clear in a video, it was impossible to locate the exact site of the event and therefore to measure the fracture distances. The videos suggested fracture propagation on the order of 50 to 100 times the length of a skier or sledder in less than 2 seconds, which closely approximates our observed velocities.

4. CONCLUSIONS

Previous fracture speed measurements on small isolated columns are lower than our video analysis of actual avalanches. While some videos had similar velocities to previous work, more videos showed much higher velocities. Our results are consistent with our observations of many avalanches over more than 40 years: fracture speed can vary widely from avalanche-to-avalanche, but the measurements from isolated beams are generally lower than what we see in the field Thus, our measurements likely better represent the range of fracture speeds observed by practitioners when triggering avalanches.

The fact that the first slab boundary to open up is the stauchwall in many of our sample videos shows that more focus may be needed in this area both from a science perspective and also on the part of practitioners.

CONFLICT OF INTEREST

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REFERENCES

Gauthier, D. and B. Jamieson. 2008. Fracture propagation propensity in relation to snow slab avalanche release: Validating the propagation saw test. *Geophysical Research Letters* 35(L13501): doi: 10.1029/2008GL034245.

Heierli, J, 2005. Solitary fracture waves in metastable snow stratifications. Journal of Geophysical Research, Vol. 110, FO2008, doi:10.1029/2004JF000178

Heierli J., Herwijnen A., Gumbsch P., Zaiser M., 2008. Anticracks: A new theory of fracture initiation and fracture propagation in snow, Proceedings of the *International Snow Science Workshop*, Whistler 2008, #8212

Johnson, B. C., J.B. Jamieson, and R. Stewart. 2004. Seismic measurement of fracture speed in a weak snowpack layer. *Cold Regions Science and Technology* 40(1-2), 41-46.

McClung, D.M. 2005. Approximate estimates of fracture speeds for dry slab avalanches. *Geophysical Research Letters*, Vol. 32, L08406 doi:10.1029/2005GL022391

McClung, D.M., 2007, Dry snow slab shear fracture speeds. *Geophysical Research Letters*, Vol. 34, L10502, doiL10.1029/2007GL029261

Miller, Dan, personal communications 2014. Montana State University Department of Civil Engineering.

Simenhois, R. and K. W. Birkeland. 2009. The Extended Column Test: Test effectiveness, spatial variability, and comparison with the Propagation Saw Test. *Cold Regions Science and Technology* 59, 210-216.

van Herwijnen, A. Fractures in weak snowpack layers in relation to slab avalanche release. 2005. *PhD thesis*, Department of Civil Engineering, University of Calgary, Calgary, Alberta. 295 pp.

van Herwijnen, A. and K.W. Birkeland. 2014. Measurements of snow slab displacement in Extended Column Tests and comparison with Propagation Saw Tests. *Cold Regions Science and Technology* 97, 97-103.

van Herwijnen, A. and J.B. Jamieson. 2005. High speed photography of fractures in weak snowpack layers. *Cold Regions Science and Technology* 43(1-2), 71-82.