EXPERIMENTS ON SELF-SUSTAINED CRACK PROPAGATION IN AVALANCHES

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ABSTRACT: If a slab avalanche is triggered, how big will it be? This question is crucial for avalanche forecasters and backcountry travelers alike, yet it is difficult to provide an answer. Indeed, little is known about dynamic or self-sustained crack propagation, the fundamental process within the snowpack that largely controls avalanche release size. Crack propagation has extensively been studied with the Propagation Saw Test (PST). However, very long PSTs (> 5m) are required to investigate self-sustained crack propagation, and it remains debatable whether the rather one-dimensional geometry of a PST influences crack propagation compared to that in real avalanches. We therefore collected data from up-slope and cross-slope PSTs, with lengths of more than 10 meters, as well as from small avalanches (12m by 12m, 35° slope) which we triggered in a controlled manner. For each field experiment, we used high-speed cameras and digital image correlation analysis of the recordings to measure displacement fields of the snowpack during self-sustained crack propagation. Our results show that the displacement fields and crack propagation speeds derived from PSTs are representative for real avalanches. Furthermore, in one experiment we observed substantially different propagation dynamics in cross-slope and up-slope direction. In cross-slope, crack propagation was driven by weak layer collapse, while in up-slope direction, we observed a transition from collapse driven to shear driven crack propagation. This is in line with recent numerical simulations that predicted a transition to so-called supershear crack propagation on steep slopes. Our unique dataset combined with the novel experimental technique allowed us to explore the emergence and dynamics of self-sustained cracks and thus allowed us to provide experimental evidence for an intensely debated process within the avalanche research community.

KEYWORDS: Avalanche release, fracture mechanics, avalanche size, dynamic crack propagation, supershear

1. INTRODUCTION

Avalanche size is a fundamental factor for predicting the regional avalanche hazard level (Schweizer et al., 2020). Moreover, at the local level, avalanche size significantly impacts the risk for winter backcountry travelers. Thus, precisely evaluating avalanche size, depending on the current snowpack characteristics, is of great relevance. Yet, this is currently a challenging task because there is limited knowledge about dynamic or self-sustained crack propagation. This fundamental process occurs within the snowpack and largely controls the size of avalanche release.

According to our current conceptual understanding of avalanche formation, self-sustained crack propagation is the final step in a sequence of fracture processes that ultimately cause the avalanche to release (Schweizer et al., 2003; Schweizer et al., 2016). While some recent studies have focused on self-sustained crack propagation, investigating this process remains challenging due to the multiple scales involved. With advancements in numerical techniques and greater computing capabilities, current numerical models can investigate crack propagation within 10 to 100 meters (Bobillier et al., 2021; Gaume et al., 2019). Such researches furnish intriguing novel perspectives (Gaume et al., 2018), such as the transition to a super-shear crack propagation mode (Trottet et al., 2021). Still, it is evident that there is a noteworthy deficiency of experimental calibration and validation data.

Collecting data on self-sustained crack propagation presents significant experimental challenges and safety concerns for investigators. The first direct measurements were obtained at the start of the 21st century, using a cumbersome seismic system to record the snow surface movement during a whumpf, i.e. self-sustained crack propagation on flat terrain (Johnson et al., 2004). With the development of the Propagation Saw Test (PST), a fracture mechanical field test became available for investigating crack propagation in snow (Gauthier and Jamieson, 2006; Sigrist and Schweizer, 2007). While numerous studies have contributed to our improved understanding of crack propagation in snow, most of them have focused on flat field measurements, revealing the limitations of the PST. Specifically, crack propagation in PSTs is may influenced by the test geometry. Experiments are commonly too short to study self-sustained crack propagation (Bergfeld et al., 2020; van Herwijnen et al., 2010). Hence, there is a pressing need for longer PSTs, preferably on steep slopes,

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and direct measurements in avalanches to study self-sustained cracks, to validate recent findings and to calibrate new models.

To tackle this need, we used the latest experimental methods to study crack propagation in snow. In the course of an exceptional phase of unpredictable snow conditions, we obtained a unique set of data on self-sustained crack propagation. Direct measurements of self-sustained cracks in small controlled avalanches, in addition to PST experiments, allowed us for to address the following questions:

How representative are the results of rather one dimensional (1D) PSTs for 2D crack propagation in real avalanches, and does the type of triggering (saw cutting or human triggering) affect crack propagation?

Are there differences in crack speeds in cross-slope and up-slope directions, and is there a terminal speed for crack propagation?

Is there a transition in crack propagation mode at a supercritical crack length, as recently suspected in numerical experiments?

2. METHODS

2.1 Field experiment

Collecting data on crack propagation in snow is always an opportunistic endeavor. It requires being at the right place at the right time, and due to safety concerns, this is often not possible. In January 2021, however, snowpack conditions were in many ways extraordinary, allowing us to easily and safely collect unique data on crack propagation in snow. We had prepared field sites in and around the town of Davos facilitating a save environment for experiments.

To prevent remote triggering of our experimental sites, we removed in advance (when the weak layer was still forming at the snow surface) the weak layer at the perimeters of each planned experiment. During the subsequent snowfalls that formed the slab, we used 1.2 m long snow saws to excavate the experimental sites from the rest of the field site. In this way we were able to not disturb the snowpack and preserve the instabilities. On 19th and 20th January, we were then able to exploit our recently developed experimental techniques (see next section) to collect data on self-sustained crack propagation in three up-slope and one cross-slope 10 m long PSTs (Figure 1a) and in two small avalanches (up to 12 x 12 m) on a 35° slope (Figure 1b). In the PSTs, we filmed the full beam width but also close-ups around the weak layer (Figure 1a, camera at the lower end of the beam), allowing for deeper insight in the processes during weak layer cracking. In the avalanche experiments, we filmed one up-slope sidewall and the bottom wall. In addition, we placed accelerometers on top of the snowpack.

2.2 Digital Image Correlation

One sidewall of each PST experiment was recorded with a high-speed camera (Phantom, VEO710, 1280 pixel horizontal resolution/ Sony Rx100M5 1920X 1080 pixel). The side wall of the PST was speckled with black ink (Indian Ink, Lefranc & Bourgeois) to enhance the contrast for digital image correlation (DIC) analysis. The camera was aligned perpendicular to the center-point of the PST beam. Camera distortion correction, DIC analysis and pre-processing (pixel to meter conversion, identifying slab, weak layer and substratum) were done as described in Bergfeld et al. (2021). For the avalanches we filmed the up-slope

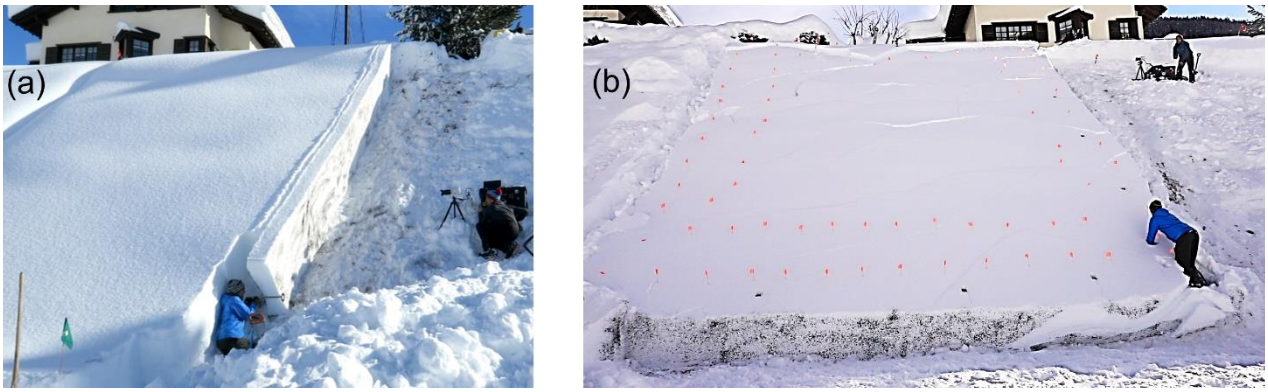

Figure 1: (a) The experimenter (person with blue jacket) cuts the weak layer of an up-slope propagation saw test (PST) with a length of 10.5 m. The experiment is filmed with a portable high-speed camera (person on the right). Left of the PST is a prepared but not yet excavated avalanche field. In its upper left corner an isolation trench, to protect the field from remote triggering, is visible. (b) The experimenter triggered an avalanche by stepping on the field with snow shoes. The crack propagated already through the whole excavated field. Slab fractures and the crown fracture are forming. The black spots on the snow surface to the left and above the experimenter are accelerometers. For digital image correlation analysis, the speckled side walls were filmed.

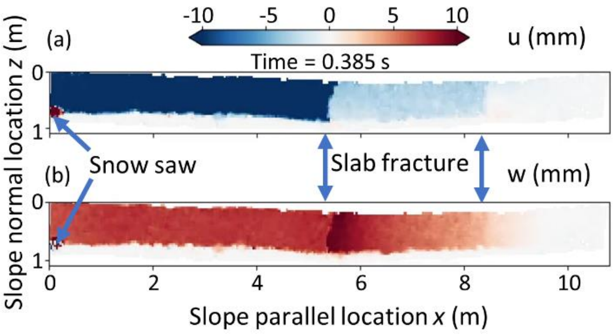

Figure 2: DIC derived displacement fields of a speckled side wall. (a) Slope parallel displacement field of a 10.5-meter-long propagation saw test. Two consecutive slab fractures become visible at around 5.5 and 8.3 meters. (b) The same slab fractures are detected in the slope normal displacement field w.

and cross slope (bottom) sidewalls of the experiment. The DIC analysis of the avalanche sidewalls was performed in the same manner as for the PST experiments.

The DIC analysis of the recorded high-speed videos provided us with slope parallel (*u*, Figure 2a) and slope normal (*w*, Figure 2b) displacement fields of the sidewalls with time. Time resolution is given by the frame rate of the recordings (250 – 8000 fps). Spatial measurement resolution (3.7- 63 mm) is given by the field of view, the step-size of the subsets, used for DIC analysis, and the pixel-to-meter conversion. The location of the crack tip was estimated for every time step applying a threshold limit for the slope normal or parallel displacement field of the slab. For a detailed description of the crack speed computation we refer to Bergfeld et al. (2023).

For the calculation of the crack speed for the close-ups, we deviated slightly from the procedure described in Bergfeld et al. (2023). The higher spatial resolution of the close-ups (3.7 mm) allowed us to localize the weak layer more accurately and to track relative displacements across the thickness of the weak layer. For the calculation of crack speed, we applied a threshold on these relative displacements. In contrast, the slope normal component of the overall slab displacement was used in the other, full-column experiments.

2.3 Accelerometers

Beside the video based DIC analysis, we also placed wireless accelerometers on the snow surface (Figure 1b, black dots on snow surface) to estimate the time the crack in the weak layer passed below.

Before triggering the avalanche, we measured the distances between the intended trigger point and each sensor using a tape measure. From the time difference and spatial distance between each pair of accelerometers, we then estimated the mean crack speed within distance. For a detailed description of the measurement devices, crack speed computation and uncertainty assessment we refer to Bergfeld et al. (2022). While Bergfeld et al. (2022) performed experiments in the flat terrain, we applied the method on inclined terrain. To retrieve the slope-parallel component of the acceleration, which can be more important in the slope, we added a signal processing step to rotate the accelerometer data such that slope normal and slope parallel accelerations can be analyzed independently.

3. RESULTS AND DISCUSSION

We performed a total of 4 PST experiments. Three experiments were 10 m long in the up-slope direction and one PST was 8 m long in the cross-slope direction. For each PST, the speed of the crack was determined from the slope normal (*w)* displacement fields. In the first 5 m of crack propagation, crack speeds were similar in all PSTs (Figure 3a). Crack speeds in the cross-slope PST and PST1 then remained relatively constant (overall mean 39 ms^{-1} and 40 ms^{-1}, respectively), while in PST 2 and 3 speeds increased to about 60 ms^{-1}. In these latter two PSTs, crack speed decreased again at slab fractures, to values close to the initial speeds. We did not measure higher crack speed values in PST1, likely due to presence of a second slab fracture earlier in this experiment (Figure 2 and Figure 3 green arrows).

In addition to the speed measurements over the entire PST length, we also recorded close-up videos in PST2 and PST3. The smaller field of view (less than a meter) increased the resolution of the measured displacements and reduced the measurement uncertainty. As an example, we were able to measure displacements of only a few micrometers. The close-up in PST2 covered an area of about 2 m < x < 2.8 m, and we measured the same crack speed as in the corresponding full-column measurement (Figure 3a, red box and red line). The close-up in PST3 was taken at about 9m of crack propagation, and the displacement field was very different from that in PST2. We did not observe the typical bending behavior of mixed-mode crack propagation. Instead, in PST3, the slab initially displaced parallel to the slope before slope normal displacements were visible. Deriving crack speeds from the slope normal displacements resulted in inconsistent and even negative results, and we therefore computed crack speed from the slope-parallel displacement component This resulted in crack speeds four to five times higher (mean 170 ms^{-1}; purple box in Figure 3a) than the mean of the other measurements. These high crack speeds and the different displacement behavior suggest that we observed crack propagation in the supershear regime. In this regime, a P-wave, propagating through the slab drives the fracture in the weak layer (Bobillier et al., 2023; Trottet et al., 2022).

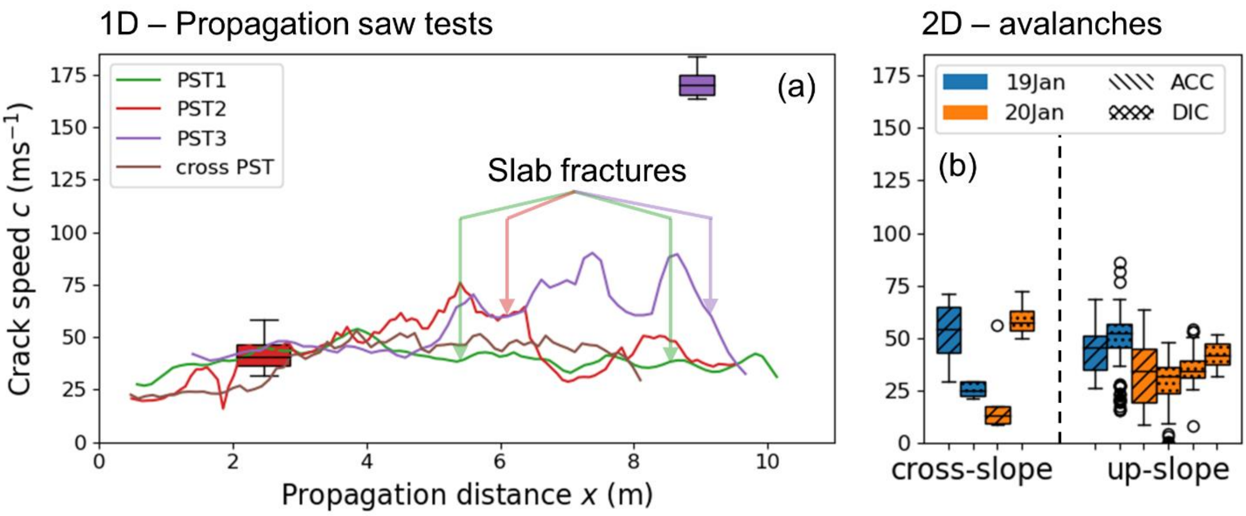

Figure 3: (a) Crack speed estimates measured in the cross-slope (brown line) PST experiment and in the three up-slope PST experiments (red, purple and green lines). The boxes stem from crack speed estimates based on the close-up recordings and follow the same color code. While in (a) crack speeds stem from 1D crack propagation in PSTs, in (b) crack speed estimates are from avalanches, hence 2D crack propagation. Two avalanches were performed (blue and orange). In both experiments we measured cross-slope and up-slope crack propagation (horizontal axis) speeds based on digital image correlation of highspeed recordings (DIC, dotted boxes) and based on accelerometers placed on the snow surface (ACC; striped hatching). Boxes represent the inter-quartile range with the middle line representing the median value

Unfortunately, we could not derive crack speeds from the slope parallel displacement in the full column experiments. There, we only resolved displacements of at least one millimeter, and such displacements were only measured when the slab started sliding. It was thus not possible to track the crack tip using the slope parallel displacement in these large experiments.

In PSTs, cracks can only propagate along the direction of the PST wall, resulting in rather one-dimensional crack propagation. Conversely, in real avalanches, the crack propagates in all directions (downslope, up-slope and cross-slope) within the weak layer simultaneously, which might result in different crack speeds. Our results, however, suggest that crack speeds observed in PSTs are very similar to those in the avalanche experiments (compare Figure 3a and 3b). Furthermore, as for the PST experiments, we did not observe substantially different crack speeds in the cross-slope or the up-slope direction (compare left and right side in Figure 3b). These results suggest that crack propagation direction (cross-slope or up-slope) or the type of trigger (snow saw or human triggered) do not affect crack speeds. Our results also confirm that PSTs can be used to study fracture processes relevant for avalanche release, provided long PST columns are used (Bergfeld 2022).

Our experiments provide valuable data on dynamic crack propagation on a steep slope, a process that has not been monitored experimentally before. The observations are very useful to qualitatively validate results from numerical simulations. For instance, we showed that for mixed-mode crack propagation, cross-slope and up-slope crack speeds were very similar, as also suggested by Trottet et al. (2022). Furthermore, data from one of the close-up experiments suggested that we also observed supershear crack propagation, as recently put forward by Trottet et al. (2022) and Bobillier (2022). The fact that we only observed this in one test does not necessarily refute this result. Indeed, the measurement resolution in the full-scale experiments was generally too low to resolve such small displacements. Furthermore, we also observed slab fractures in most of our experiments, and these slow down the crack, as also suggested by the numerical study of Bobillier (2022). Overall, our experiments thus provide valuable new insights into dynamic crack propagation, and show that this complex process still holds many secrets that need to be unravelled.

4. CONCLUSION AND OUTLOOK

Self-sustained crack propagation is one of the most intensely debated topics in the avalanche research community. Typically, crack propagation in weak layers has been investigated with propagation saw tests. Until now, however, it was largely unknown whether the special geometry of the PSTs also affects crack propagation and whether the observed processes are similar to those occurring in real avalanches. Furthermore, the triggering method of a PST (sawing into the weak layer) is not the same as how avalanches are typically triggered. To investigate these issues, we performed PSTs next to small, controlled avalanche experiments and investigated them with video-based digital image correlation analysis and accelerometers placed on the snow surface. Our experiments provide much needed benchmark data for numerical models. Based on our results, we can draw the following conclusions:

1. Displacement fields and crack speeds observed in PSTs are very similar to those observed in the small avalanches.

2. Crack speed of cross-slope crack propagation is similar to mixed-mode crack propagation in up-slope direction.

The concept that cracks in the weak layer could propagate at much greater speeds, in a so-called supershear crack mode, was recently suggested based on numerical simulations (Trottet et al., 2022). The analysis of our data seems to suggest that such a mode may indeed exists, although we made these observations only in a single experiment. In the future, more field experiments are required in which close-up displacement fields are recorded with high-speed cameras to confirm this single observation, and provide more insight into the complex processes involved in dynamic crack propagation in snow.

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