DEVELOPING TWO MULTIAXIAL TESTING MACHINES TO LINK STRENGTH AND MICROSTRUCTURE OF WEAK SNOW LAYERS

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ABSTRACT: Avalanche forecasting increasingly relies on snow cover models. In this context, accurate information on the mechanical properties of weak layers is required to better represent the failure and fracture processes leading to avalanche release. In order to accurately determine these material properties, and link those to snow microstructure, we have developed two displacement-controlled testing machines to perform strength tests under multiaxial loading conditions. The first experimental setup is for field measurements, allowing us to test many samples of the same natural weak layer. The second experimental setup is for laboratory experiments where we can perform precise measurements in a controlled environment on a limited number of artificially created weak layers. Here we present both machines as well as some of the challenges we faced in designing them.

Keywords: snow slab avalanches, weak snow layers, snow strength, experimental testing, microstructure

1. INTRODUCTION

Slab avalanches are responsible for the majority of avalanche fatalities, which makes them most relevant for avalanche forecasting (e.g. Schweizer and Jamieson, 2001). Since the processes involved in slab avalanche release are relatively well known, models are increasingly used in avalanche forecasting. However, such models require detailed knowledge of the mechanical properties of snow, and in particular weak layers. To date, mechanical properties are often parameterized based on density and do not explicitly consider snow microstructure (e.g. Jamieson and Johnston, 2001).

To model the initiation of slab avalanches, weak layer strength is a crucial parameter. It is therefore necessary to have a failure criterion for weak layers that incorporates natural loading conditions, ranging from pure compression to pure shear stress states. Previous experimental studies have found a dependence of the shear strength of weak layers on the applied normal force and have proposed (modified) Mohr-Coulomb criteria (e.g. Reiweger et al., 2015; Mellor, 1975). Recent numerical approaches based on FEM and DEM proposed elliptical failure envelopes (e.g. Singh et al., 2022; Bobillier et al., 2020; Ritter et al., 2020; Mulak and Gaume, 2019; Mede et al., 2018). Nevertheless, the experimental data in the literature are sparse and often limited by the experimental setup (e.g. use of dead weights and load-controlled experiments). Furthermore, the influence of snow microstructure has not been investigated in detail. It is well known, that snow properties can differ by orders of magnitude for the same density based on microstructure (e.g. Mellor, 1975), making it a significant blind spot in current modeling approaches.

Mechanical testing of weak layers can be a challenging task. Their properties are highly sensitive to temperature and displacement rate, and microstructural properties may change during the experiment (e.g. Camponovo and Schweizer, 2001). Furthermore, transporting natural weak layers to a cold laboratory can be difficult due to their fragile nature. Testing weak layers in the field was limited so far to determining shear strength by pulling shear frames (e.g. Föhn, 1987) or deriving mechanical properties from snow micro-penetrometer (SMP) measurements (e.g. Reuter et al., 2015). To address these challenges, we developed two displacement-controlled testing machines to perform strength tests under multiaxial stress conditions both in the field and in the laboratory. The microstructure of the snow samples is characterized from micro-computed tomography (μCT) images (e.g. Coléou et al., 2001), which will ultimately enable us to link the multiaxial strength of weak layers to their microstructure.

2. PORTABLE MACHINE FOR THE FIELD

While weak layers in a natural snowpack provide an almost unlimited supply of samples for experimental

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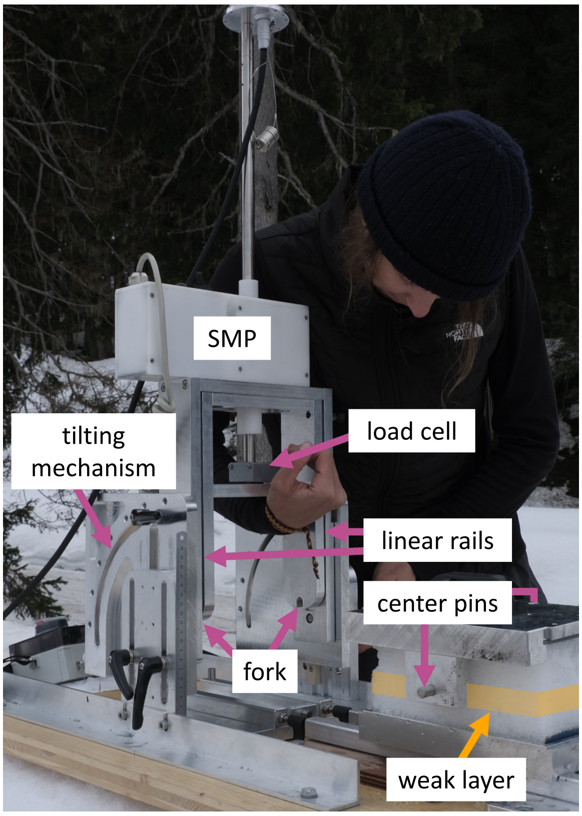

Figure 1: Portable testing machine setup for a compression experiment in the field.

testing, there are substantial limitations to the quality of the data collected. First, field experiments depend on the presence of weak layers in the snowpack that are persistent enough to allow for multiday measurement campaigns. Second, field experiments are exposed to environmental conditions that can affect the measurement results, such as temperature or solar radiation. Third, the limited equipment available during field experiments restricts the quality of the experimental data. While in the laboratory we can use specialised tools to measure, handle and prepare snow samples (e.g. μCT scanner, band saw, electric power), in the field this infrastructure is either lacking or difficult to access. Therefore, sample preparation and testing may be less precise, thereby introducing more scatter in the data. Mechanical experiments in the field are thus more error-prone and therefore require many repetitions to produce comprehensive results.

To test a large number of samples in the field, we developed a portable machine specifically designed to meet these challenges (Figure 1). The machine weighs about 15 kg and is based on the electronics of the SMP (Schneebeli and Johnson, 1998) attached to a custom-built tilting mechanism. This allows us to change the loading angle and, consequently, the effective multiaxial stress state within the weak layer. The device is coupled to the snow sample using interface plates with pins and fins.

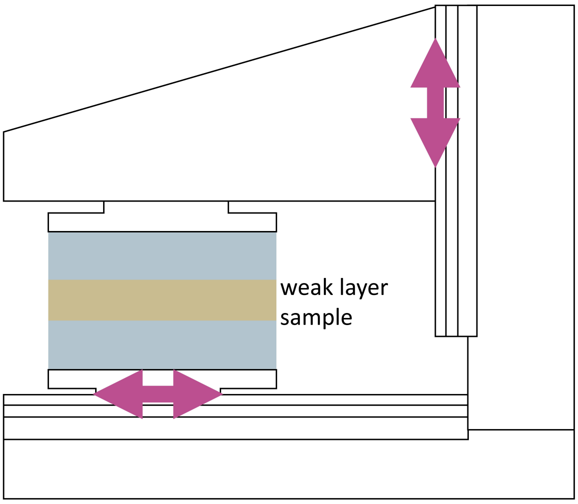

Figure 2: Sketch of the second, two-channel testing machine

3. PRECISION MACHINE FOR THE LABORATORY

In the cold laboratory, many of the challenges associated with field campaigns can be avoided. We can control the temperature, we have flat and level surfaces to work on, and all the infrastructure needed to prepare samples and quantify snow microstructure is readily available. The main challenge, however, is the availability of representative snow samples. These must either be carefully transported from the field to the laboratory or created artificially. Mechanical experiments in the laboratory are thus limited by the number of weak layer samples available, and therefore prioritize quality over quantity.

To test snow samples in the laboratory, we developed a second machine, custom-built for use in a cold environment. As the machine is not yet finished, we only show a sketch of the concept at this point (Figure 2). The effective stress state within the weak layer is driven by the combined displacement along two independent axes. Each axis is equipped with a linear motor, linear rails, a high-precision load cell and linear encoders. To ensure a good connection between the snow sample and the machine, we will attach interface plates to the snow samples. The machine is capable of compensating for misalignment of the sample surface, ensuring an even load distribution throughout the weak layer. It will enable us to test the strength under multiaxial loading conditions of both natural and artificial weak layers with high accuracy.

4. MICROSTRUCTURE

We use μCT images to reliably quantify snow microstructure of samples from the field and laboratory experiments. For the field experiments, we cut the samples to size and transport them in a sample holder in a cushioned styrofoam box to the lab.

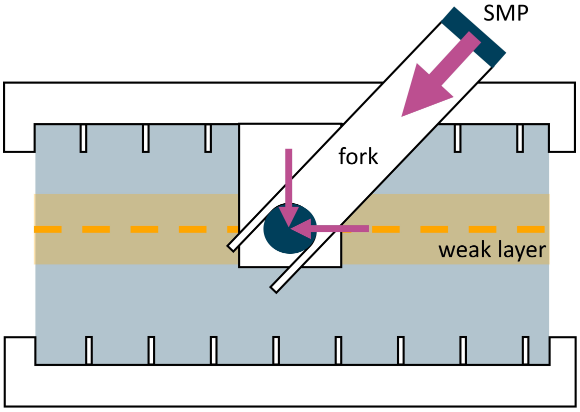

Figure 3: Constructive design to convert a uniaxial displacement into a multiaxial stress state within the weak layer. The large arrow represents the force applied by the SMP, which results in a multiaxial stress state without moments in the middle of the weak layer. The upper and lower plates are sample attachment plates with pins and slats to ensure good connection to the sample.

In order to avoid breaking the fragile weak layers during sample preparation and transport, we use sample holders with diameter 50 mm, 70 mm and 90 mm, depending on how fragile the weak layers are. The effective resolutions (voxel size) is then $(16.2\ \mu\text{m})^3$, $(22.8\ \mu\text{m})^3$, and $(29.1\ \mu\text{m})^3$, respectively. These scans allow us to retrieve density and specific surface area (SSA) with high accuracy and to derive further quantities such as directional correlation lengths and to quantify the degree of anisotropy in the weak layer.

5. DISCUSSION

Development of both machines began in 2022 and was inspired by previous multiaxial weak layer experiments (Capelli et al., 2018; Reiweger and Schweizer, 2010). There are two practical ways to apply displacement-controlled multiaxial stress to a snow specimen: (1) a one-channel setup that can be rotated around the center of the weak layer, as in our field setup, and (2) a two-channel setup where the superposition of two perpendicular displacements results in a multiaxial stress state, as in our laboratory setup.

The portable machine uses setup (1), which allowed us to reduce the size and weight of the machine. However, to avoid unwanted moments in the weak layer, the point of force application must be aligned with the weak layer. We achieved this by applying the force to the upper part of the specimens using two forks in contact with pins at the level of the weak layer (see Figure 3). If the specimens are not prepared to the correct dimensions, or if the failure does not occur on a horizontal line passing through the pins, this can lead to measurement uncertainties. Preliminary tests in February 2024 highlighted the importance of carefully preparing and inserting the samples in the machine. The high-precision machine uses setup (2), which gives us more experimental design options and simplifies the test procedure and data acquisition.

6. OUTLOOK

The portable machine was designed and built in-house at the SLF workshop. A first version was tested in the field in winter 2023/24 and will be further upgraded to improve data quality and workflow. For the development of the high-precision machine, we collaborated with the Institute for Materials and Technological Processes (University of Porto). We plan to conduct measurement campaigns with both machines in the coming winters. This combination of field experiments (with a large number of samples available) and laboratory experiments (with high precision and thus high quality data) will result in a large data set that should allow us to quantify the strength of weak layers under multiaxial loading conditions and the influence of microstructure. Such data are needed for the next generation of snowpack and avalanche release models.

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