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Field measurements of multiaxial strength of weak snow layers

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Abstract

Dry-snow slab avalanche release is initiated by a failure in a buried weak layer. Quantifying the multiaxial strength of weak snow layers is therefore essential, yet field measurements remain scarce compared to laboratory or numerical studies. We developed a mobile testing machine to quantify the multiaxial strength of weak snow layers in the field. We measured the strength of two layers of buried surface hoar: SH24 (43 samples) and SH25 (75 samples), and derived the corresponding failure envelopes. Even though the strength values exhibited considerable scatter, the data were described by an elliptical failure envelope. Compressive strength exceeded shear strength for both layers, with higher strength values for SH24 ($\sigma_c = 7.9 \pm 0.6$ kPa, $\tau_c = 5.8 \pm 0.4$ kPa) compared to SH25 ($\sigma_c = 5.0 \pm 0.3$ kPa, $\tau_c = 3.5 \pm 0.2$ kPa). Micro-computed tomography analysis revealed differences in microstructural parameters, most notably indicating that SH25 had a finer and more connected structure. Video-based digital image correlation showed that the effective strain rates in the weak layers were on the order of 10^{-3} s^{-1} and typically larger in shear than in compression. This work provides multiaxial strength data of weak layers, valuable for comparison with laboratory experiments and for informing numerical models.

1. Introduction

Dry-snow slab avalanches are a major hazard in alpine regions and are responsible for most avalanche-related fatalities worldwide (Techel and Zweifel, 2013). Assessing dry-snow slab avalanche hazard relies heavily on identifying and characterizing weak layers in the snow-pack. Information on their presence, structure and mechanical properties is therefore central to avalanche forecasting, particularly when recent avalanche activity is absent. To support this assessment, manual field observations such as snow profiles and stability tests are widely used, and correlations with avalanche likelihood have been documented (e.g. Schweizer and Jamieson, 2007; van Herwijnen and Jamieson, 2007). However, the subjectivity of some manual indices, such as hand hardness or grain size, limits their ability to provide a clear and direct link to the material properties of snow. Objective measurements of weak layer strength are thus essential for improving snow stability evaluation.

Early mechanical characterization of weak layers focused primarily on shear strength, reflecting the conceptualization of slab avalanche release as a balance between shear loading imposed by the overlying slab and shear resistance of the weak layer (e.g. Perla and others, 1982; Föhn and others, 1998). Numerous field and laboratory methods were developed (e.g. Perla and Beck, 1983; Schweizer, 1998; Jamieson and Johnston, 1999; 2001; Jamieson and Schweizer, 2000) to quantify shear strength, and these measurements formed the basis of many traditional stability assessments. However, natural weak layers are rarely subjected to pure shear. Instead, they typically experience combined compressive and shear stresses arising from slab geometry, loading conditions and deformation of the snowpack, indicating that shear strength alone provides an incomplete description of their failure behavior.

This recognition prompted a fundamental shift in the understanding of slab-avalanche release mechanisms. The anticrack concept (Heierli and others, 2008) and subsequent experimental and theoretical work demonstrated that weak layer failure involves a complex interaction between compression and shear, rather than shear alone (e.g. Gaume and others, 2014; Rosendahl and Weißgraeber, 2020). This motivated the representation of weak layer strength in a combined stress space, where failure envelopes define the combinations of normal and shear stress leading to failure (e.g. Reiweger and Schweizer, 2010; Chandel, 2014; Reiweger and others, 2015).

Initial multiaxial representations of weak layer failure often employed a Mohr–Coulomb-type criterion, adapted from geotechnical engineering (e.g. Gaume and others, 2013),



which forms an open linear failure envelope in stress space. Subsequent experimental observations showed that weak layers can also fail under compressive loading, implying that failure envelopes must be closed in stress space. To address this, Reiweiger and others (2015) proposed a capped Mohr–Coulomb criterion based on load-controlled multiaxial experiments on different types of weak layers (e.g. Reiweiger and Schweizer, 2010). In parallel, an elliptical envelope shape was introduced by Chandel (2014), later supported by numerical simulations (e.g. Chandel and others, 2015; Mede and others, 2018; Mulak and Gaume, 2019; Bobillier and others, 2020) and, more recently, by displacement-controlled laboratory experiments (Schöttner and others, 2026). Together, these studies highlight the importance of combined shear and compressive stress interactions in weak layer failure.

Despite these advances, experimental investigations of multiaxial weak layer strength remain constrained by practical limitations. Multiaxial laboratory experiments (e.g. Reiweiger and others, 2015; Schöttner and others, 2026) require careful sample preparation and handling, which restricts the number of samples that can be tested and limits systematic exploration of loading angles. Investigating the influence of weak layer microstructure further increases experimental demands and inherently requires an even larger number of samples (e.g. Schöttner and others, 2025). Numerical simulations have therefore played an important complementary role in exploring mixed-mode stress interactions across a broader parameter space (e.g. Chandel and others, 2015; Mede and others, 2018; Mulak and Gaume, 2019; Bobillier and others, 2020). As a result, our current understanding of multiaxial weak layer strength relies largely on laboratory experiments and numerical simulations, whereas direct measurements under natural snowpack conditions remain rare. In particular, measurements of weak layer strength under combined shear and compressive loading in the field are still largely missing, despite their relevance for real avalanche release scenarios. Bridging this gap is essential for linking laboratory insights and numerical models to natural snowpack behavior.

The present study addresses this gap by performing measurements of the multiaxial strength of natural weak layers in the field and determining the failure envelopes. We introduce a mobile shear–compression testing machine where the load was applied in displacement control to measure the strength of weak layers under loading angles ranging from predominantly shear loading to pure compression. Mechanical measurements were complemented by micro-computed tomography (μ CT) analyses of snow microstructure and are directly compared with laboratory results for one weak layer previously investigated by Schöttner and others (2026).

2. Methods

To obtain failure envelopes of natural weak layers, we conducted loading experiments in the field to assess weak layer strength under multiaxial stress states. We used video recordings to qualify experimental issues, identify the moment of failure and determine the effective strain rate across the weak layers. Additionally, we investigated the effective loading angle in the weak layer using a finite element (FE) model. Finally, we characterized the snow microstructure through μ CT.

2.1. Field sites and weak layers

Field experiments were conducted at two sites above Davos, Switzerland, in February 2024 and February 2025 (Table 1). In

2024, tests were performed on a 6-week-old layer of buried surface hoar near the Flüela creek at an elevation of 1634 m a.s.l. In 2025, a 4–5-week-old layer of buried surface hoar was tested at Steintälli (2443 m a.s.l.) over 6 consecutive days between 23 and 28 February. At both sites, the weak layers consisted of surface hoar crystals with grain sizes of 3–8 mm overlain by a cohesive slab. Snowpack properties were documented using standard snow profiles following Fierz and others (2009) and with snow micro-penetrometer measurements (Schneebeli and Johnson, 1998).

Weak layer microstructure was characterized using μ CT (Schneebeli and Sokratov, 2004). For this purpose, samples containing the weak layer were carefully extracted in the field, placed into rigid sample holders and insulated in styrofoam boxes filled with snow to minimize temperature gradients and mechanical disturbance during transport. Samples were transported to the cold laboratory within the same day, and scans (μ CT90, Scanco Medical) were performed at a voxel size of 29.1 μ m. A cubic ROI containing only the weak layer was selected, and density, specific surface area (SSA), correlation lengths, vertical anisotropy, connectivity density, local thickness, tortuosity, mean curvature H ($(\kappa_1 + \kappa_2)/2$) and mean Gaussian curvature K ($\kappa_1\kappa_2$) were derived from the binarized three-dimensional (3-D) data following established methods (Schneebeli and Sokratov, 2004; Schlee and Löwe, 2013; Calonne and others, 2014; Schöttner and others, 2025).

2.2. Multiaxial loading machine and testing procedure

Mechanical tests were conducted in the field using a custom-designed mobile shear–compression unit (MSCU; Fig. 1). The device enables loading of snow samples at adjustable angles, allowing investigation of weak layer strength under combined shear and compression loading. The MSCU consists of a linear loading unit, adapted from the SnowMicroPen (SMP5 version, SLF (2025)), equipped with a calibrated force sensor (piezoelectric load cell from Kistler Instrumente AG, type 9313AA1, series 643364) mounted on a loading frame. The loading frame is positioned inside a tilting frame that allows the loading angle α to be adjusted between 0° (parallel to the weak layer, shear-dominated loading) and 90° (perpendicular to the weak layer, compression-dominated loading). The applied displacement from the loading unit is transmitted via a rigid loading frame to a lid resting on top of the snow sample. All components are mounted on a rigid base plate to ensure stable operation under field conditions. The outer tilting frame carries its own weight. However, in the setup used for testing SH24, the mass of the loading frame, which is mounted in the tilting frame, exerts a load on the sample, whereas in the SH25 configuration, this load was compensated for by a spring system. Snow samples were extracted as intact blocks from the pit wall with dimensions of 10 cm (width) $\times$ 20 cm (length) $\times$ 8–10 cm (height), with the weak layer centered between a cohesive slab of approximately 5 cm thickness and a supporting substratum (Fig. 1d). After extraction, samples were stored in the shade and tested within 5 min to minimize thermal and mechanical alteration.

A key aspect of the experimental setup was the mounting and constraining of the snow samples within the loading system. Each sample was first placed into a rigid bottom sample holder. To prevent horizontal sliding during loading, metal inlays, coupled to the bottom holder, were inserted into the stiffer snow below the weak layer (Fig. 1e). A rigid lid was then placed on top of the sample and similarly equipped with metal inlays inserted into the stiffer snow above the weak layer to prevent relative horizontal motion

Table 1. Properties of the weak layers tested and the machine settings.

	SH24 (2024)	SH25 (2025)
Measurement location	Flüela valley 1634 m a.s.l	Steintälli 2443 m a.s.l
Field site coordinates (WGS 84)	46.80773° N, 9.86999° E	46.808393° N, 9.790975° E
Weak layer crystal type, grain size (mm)	SH, 5–8	SH, 3–6
WL age at day of testing	6 weeks	4–5 weeks
Days of measurements	14 February 2024	23–28 February 2025 (6 consec. days)
Loading rate (mm s^{-1})	0.15	1.65
Mass of lid (kg)	2	0.35
Material of lid	Aluminum	3-D printed
Mass of loading frame (kg)	1.6	N/A (*)
Spring system	No	Yes

Note: *In 2025, the loading frame was carried by a spring system and therefore did not exert any force on the sample.

between the lid and the snow sample (Fig. 1f). In addition, horizontal inlays were inserted into the stiffer snow layers above and below the weak layer to limit vertical movement of the sample relative to both the bottom holder and the lid. This mounting configuration was designed to constrain rigid-body motion of the sample while allowing deformation and failure to localize within the weak layer.

The mounted sample, including bottom holder and lid, was subsequently positioned below the loading unit and aligned with the rigid loading frame such that the applied displacement acted at the height of the weak layer. The bottom holder was firmly locked in place on the base plate. For loading angles $\alpha \leq 30^\circ$, additional stabilizers and clamps were used to prevent upward tilting of the lid during shear-dominated loading (Fig. 1j).

The load was applied in displacement control at a constant rate until failure of the weak layer occurred. The presence of the vertically aligned inlays affects the transmission of the applied loading onto the sample. The contact between the loading frame and the pins of the lid is nonrigid, introducing a degree of freedom in the loading transmission. Force and displacement were recorded continuously throughout each experiment.

Two datasets were collected in consecutive winters with some modifications to the loading system. In 2024 (SH24), the weight of the aluminum lid exerted an additional vertical load of 2.0 kg on the sample. Additionally, the weight of the loading frame (1.6 kg) exerted an additional load in the loading direction. In 2025 (SH25), a spring system was introduced to carry the weight of the loading frame (Fig. 1a,c), such that only the weight of a lighter 3-D-printed lid (0.35 kg) acted on the sample. The imposed displacement rate was 0.15 mm s^{-1} for SH24 and 1.65 mm s^{-1} for SH25. For a sample thickness of 10 cm, this corresponds to nominal strain rates of $1.5 \times 10^{-3} \text{ s}^{-1}$ and $1.65 \times 10^{-2} \text{ s}^{-1}$, respectively. Despite the applied constraints, small variations in load transmission and boundary conditions between experiments are unavoidable and represent a primary source of experimental scatter.

2.3. Video-based experiment validation and failure identification

All experiments were recorded from the long side of the sample using a digital camera operating at 50 frames per second. Due to the machine design, approximately 50% of the long side of the sample was visible on camera. The video recordings were used to qualitatively assess the test validity and to identify the moment of failure. Experiments were discarded if failure occurred outside the targeted weak layer, for example, within the slab or the substratum, or if excessive rigid-body motion of the snow sample relative to the lid or bottom holder was observed. Only experiments that satisfied these criteria were included in further analysis.

For the experiments retained, weak layer failure was typically characterized by a sudden and pronounced failure and collapse of the weak layer, clearly visible in the video recordings (Fig. 2). This failure was accompanied by rapid relative displacement of the slab and a distinct force peak followed by a drop in load (Fig. 2d). The moment of weak layer failure was used to synchronize the video recordings with the force–displacement signals, and the corresponding force peak was selected for subsequent stress calculations. This alignment between video and force signal allowed us to link specific events, such as the settling of the substratum, to certain force pop-ins.

Many experiments exhibited abrupt force drops that were not associated with weak layer failure. These artifacts were caused by progressive rearrangement of the mounting system, for example, when metal inlays in the lid or bottom holder were not fully seated at the beginning of loading and were further pushed into the surrounding snow during the experiment. Such events produced sudden drops in the force signal but were not accompanied by failure of the weak layer in the video recordings. Such events are called pop-ins, as reported in other snow experiments (e.g. Schöttner and others, 2025). Figure 2 shows a representative example. The synchronized use of video and force data, therefore, allowed reliable distinction between true weak layer failure and mounting-related artifacts, ensuring consistent identification of failure across experiments.

2.4. Stress state and failure envelope determination

2.4.1. FE analysis of the effective stress state in the weak layer

Although we can prescribe a nominal loading angle α with the MSCU, the actual stress state in the weak layer depends on load transfer through the lid, the material properties of the slab, weak layer, and substratum, as well as small geometric imperfections such as lid tilting or uneven settling of the mounting system. To assess the resulting stress state in the weak layer and quantify the sensitivity of the stresses to boundary effects, we conducted FE model parameter studies using the Abaqus/CAE 2023 software (Dassault Systèmes Simulia Corp, 2023).

The snow sample was idealized as a 3-D, linear-elastic, three-layer system consisting of a substratum, a weak layer and an overlying slab. The sample measured $200 \times 100 \times 100 \text{ mm}^3$. All deformable regions were discretized with eight-node linear hexahedral elements with reduced integration (C3D8R). A global element size of 4 mm was used in the sample.

The base of the substratum was fully fixed (all displacement degrees of freedom constrained). The rigid lid was tied (bonded, no relative sliding) to the top of the slab, and load was transferred to the lid through two discrete contact points representing the pins,

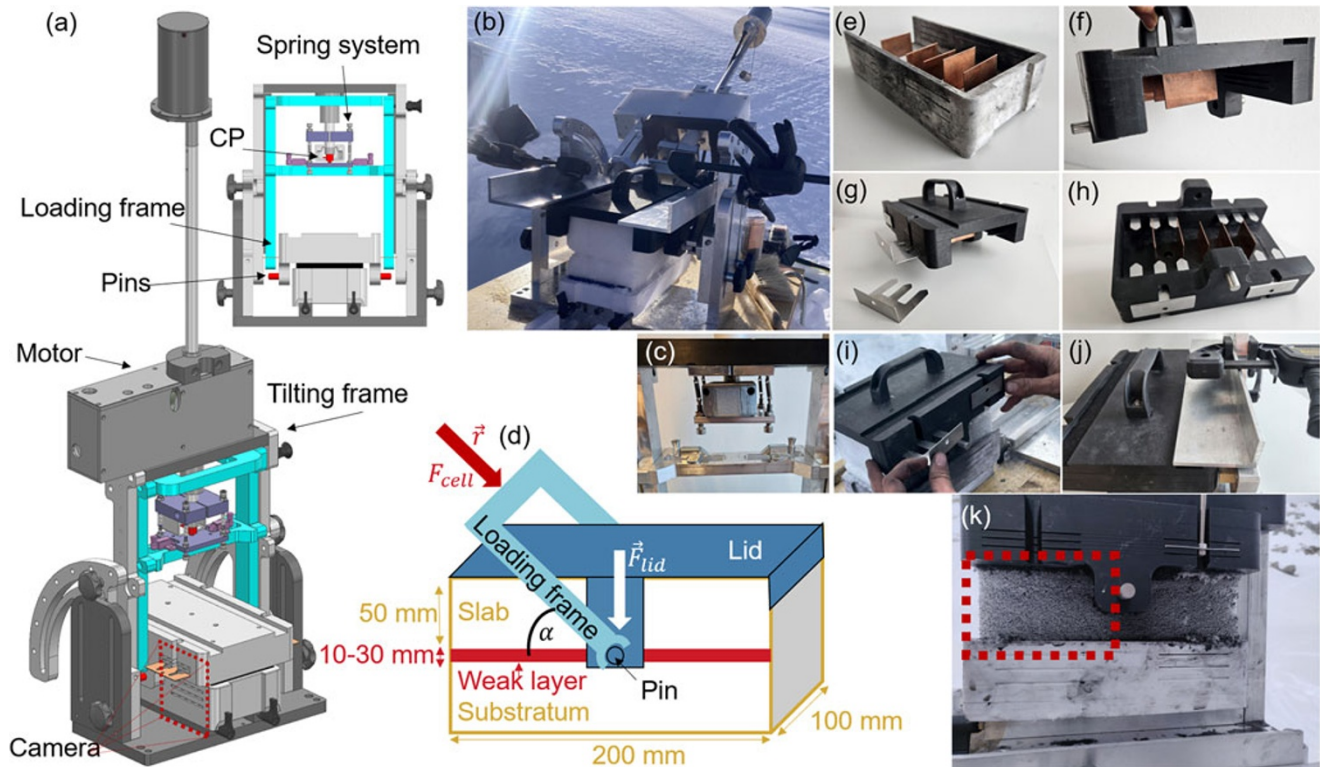


Figure 1. (a) Schematic overview of the MSCU, with the newly added (in 2025) spring system highlighted in purple. The red point inside the spring system is the contact point (CP) of the motor unit to the lower plate of the spring system, which is part of the loading frame (in turquoise). The pins of the lid, on which the loading frame applies force, are also highlighted in red. The camera view is presented by the dotted red square. (b) Picture of the MSCU in use in the field, with additional stabilizers and clamps used for loading angles $\alpha \leq 30^\circ$. (c) Close-up of the spring system, which is mounted around the rod of the motor unit. Here, the loading frame is not yet connected to the spring system. Additional pictures are in Appendix Figure A3. (d) Schematic overview of the sample with the lid and the tilting frame. The load cell moves down on the tilting frame, which pushes around the pins under various loading configurations from $\alpha = 0^\circ$ (shear) to $\alpha = 90^\circ$ (compression). The lid creates an additional vertical force F_{lid} on the sample, and the loading frame creates an additional force F_{lf} in the direction of loading. Vertical metal inlays are in the bottom holder (e) and in the lid (f). Horizontal inlays are inserted in both the bottom holder and the lid (g), (h) and (i). (j) shows how the additional stabilizers are positioned above the lid. (k) The red frame highlights again the camera view of the sample, prepared inside the lid and bottom holder.

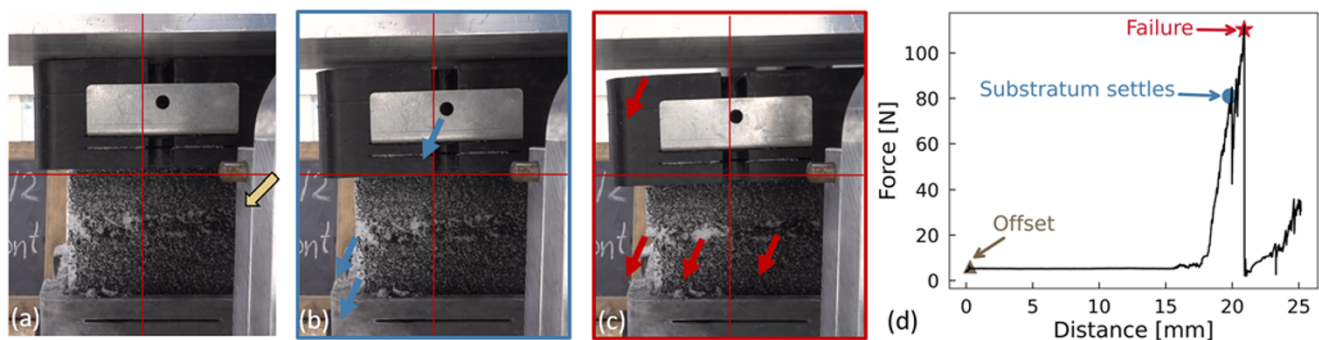


Figure 2. (a–c) Images of a representative experiment loaded at 45° (SH25-1365). (a) Before loading, the yellow arrow indicates the direction of loading. (b) The sample first settles further into the bottom sample holder (blue circle in d). (c) The weak layer fails (red star in d). The axes and arrows highlight changes relative to the previous image. (d) The force signal versus the distance covered by the loading frame. Indicated are the offset (brown triangle) caused by the first contact between the loading frame and the sample, substrate settling (blue circle) and weak layer failure (red star).

each connected to the lid by a distributing coupling. This configuration reflects the essential load path of the experimental setup while allowing controlled variation of key parameters.

Two loading configurations were considered: (1) displacement boundary conditions (DBC), in which a displacement was prescribed at the contact points, and (2) force boundary conditions (FBC), in which a force was applied at the two contact points instead. Comparing these boundary condition types allows us to

assess the sensitivity of the resulting stress in the weak layer to assumptions about the loading constraints imposed by the experimental setup. Each simulation was solved in a single static step from the unloaded to the loaded state. The loading direction was varied between 0° and 90° in increments of 5° by decomposing the applied load into components normal and tangential to the weak layer. Because linear elasticity was assumed, all stresses scale linearly with the applied load. The absolute magnitude of the applied

force or displacement therefore did not affect the stress distribution and was set to an arbitrary reference value.

For each simulation, we extracted the stress tensor at the element integration points within the weak layer from the final (fully loaded) increment. Because C3D8R elements have a single integration point, these correspond to element-centroidal stresses; no extrapolation to nodes or nodal averaging was applied. We denote by σ the stress component normal to the weak layer (Abaqus component S33) and by τ the in-plane shear component (S13). To obtain a single representative (σ, τ) pair per simulation, we spatially averaged these components over the weak-layer elements whose centroids lay within the central 80% of the layer's in-plane extent, excluding a margin along each edge to remove boundary stress concentrations (St Venant effects). Because the weak layer used a uniform structured mesh, this arithmetic mean is equivalent to a volume-weighted mean.

From these averaged stresses, we defined an effective loading direction $\alpha_{\text{eff}} = \arctan(\tau/\sigma)$, i.e. the ratio of shear to normal stress in the weak layer. The resulting effective loading angles were then used to compute stress components and to fit the failure interaction law, which we compared against the interaction law fitted to the raw stress data using the nominal loading angle $\pm 2^\circ$.

We systematically varied (i) the elastic-modulus ratio between the weak layer and the slab (1:2, 1:5, 1:10); (ii) the Poisson's ratio of the weak layer and slab (0.1, 0.2, 0.3, 0.4, changed simultaneously); (iii) the distribution of load between the two contact points to mimic uneven load transfer (100:100, 110:100); and (iv) lid tilting observed in our experiments ($-2, 0, +2^\circ$). For each parameter combination, we evaluated σ and τ as described above.

2.4.2. Stress calculation at weak layer failure and failure envelope

For each retained experiment, the force peak associated with weak layer failure was identified using synchronized video recordings and force–displacement data. Stresses at failure were calculated by decomposing the measured peak force into shear and compressive components acting on the weak layer. Specifically, the shear stress τ and compressive stress σ at failure were computed as

$$\begin{aligned}\tau &= \frac{(F_{\text{cell}} - F_{\text{offset}}) \cos(\alpha) + F_{\text{lf}}^h}{A}, \\ \sigma &= \frac{(F_{\text{cell}} - F_{\text{offset}}) \sin(\alpha) + F_{\text{lf}}^v + F_{\text{lid}}^v}{A},\end{aligned}\quad (1)$$

where α is the loading angle, F_{cell} denotes the force measured by the load cell and F_{offset} is a constant force offset present prior to loading of the snow sample. The offset contains the constant extension of the springs and internal friction. The springs are loaded once the motor unit touches the springs, and this pressure remains constant during loading. Internal friction arises within the loading frame and contact friction between the rigid loading frame and the pins of the lid and is measured as soon as the loading frame comes into contact with the lid before any deformation of the snow sample occurs. As the offset does not contribute to stress within the weak layer, it was subtracted from the measured force signal prior to identifying the peak force associated with weak layer failure. The parameter A is the planform area of the sample ($A = 0.02 \text{ m}^2$). F_{lf}^h is the horizontal component of the weight of the loading frame for SH24 ($F_{\text{lf}} \cos(\alpha)$), and equals 0 for SH25 as the spring system carries the weight of the loading frame. Similarly, F_{lf}^v is the vertical component of the weight of the loading frame for SH24 ($F_{\text{lf}} \sin(\alpha)$), and equals 0 for SH25. F_{lid}^v is the additional normal force resulting from the dead weight of the lid (F_{lid}).

Uncertainties in σ and τ were propagated using the Python uncertainties package (Lebigot, 2024). The uncertainty in α_{eff} was estimated based on the FE parameter study and accounts for deviations caused by uneven load transfer and mounting-related imperfections. Additional parameter uncertainties of $F_{\text{load}} \pm 0.1 \text{ N}$, sample width $\pm 0.005 \text{ m}$ and sample length $\pm 0.01 \text{ m}$ were included in the error propagation.

To quantify multiaxial weak layer strength, the stress states at failure were fitted with an elliptical failure envelope in the σ – τ stress space. Following previous experimental work on snow weak layers (e.g. Chandel, 2014; Schöttner and others, 2026), failure can be described by

$$\left(\frac{\sigma}{\sigma_c}\right)^2 + \left(\frac{\tau}{\tau_c}\right)^2 = 1, \quad (2)$$

where stresses σ and τ are the applied stresses (Eqn (1)) and σ_c and τ_c are the fit parameters and denote the compressive and shear strength under pure loading conditions, respectively. The parameters σ_c and τ_c were estimated using orthogonal distance regression (ODR) as implemented in *scipy.odr* (Virtanen and others, 2020), which wraps the ODRPACK library (Boggs and others, 1989), to account for uncertainties in both stress components. Stress values below the experimental resolution were treated as $\tau = 0$ with an uncertainty equal to the measurement resolution (0.2), thereby avoiding artificial numerical precision while preserving the statistical weight of near-pure compression experiments in the regression.

2.5. Strain rate estimates

To estimate the effective strain rates in the weak layer during loading, we analyzed a subset of experiments using digital image correlation (DIC) (Turner and others, 2015). Two regions of interest (ROIs) were defined directly above and below the weak layer (Fig. 3a) with a typical size of $60 \times 6 \text{ mm}^2$, and the *tracking* analysis mode was used to extract horizontal (u_x) and vertical (u_y) displacements as well as the in-plane rotation β_z for each ROI (Fig. 3b). The correlation quality ('gamma' in DIC) was typically around 10^{-5} , and the estimated uncertainty ('sigma' in DIC tracking) was 10^{-3} px (taken from representative experiment SH25-1332). A ruler allowed conversion from pixels to physical dimensions. The typical scaling factor was 8 px/mm , and the temporal resolution was 50 fps. The physical displacement uncertainty was estimated to be 10^{-4} mm by multiplying the typical DIC tracking uncertainty with the scale factor.

Effective strains across the weak layer were calculated from the difference in translational displacement between the upper and lower ROI, Δu_x and Δu_y , over a short interval immediately preceding failure (Fig. 3). The positive y -direction was defined downward in the direction of gravity and the positive x -direction perpendicular to the y -direction, such that the horizontal loading component was positive, and rotations were defined as counterclockwise.

Compressive strain ε_{yy} and shear strain γ across the weak layer were then computed as:

$$\varepsilon_{yy} = \frac{\Delta u_y + \beta_z \Delta x}{h_{\text{WL}}}, \quad \gamma_{xy} = 2\varepsilon_{xy} = \frac{\Delta u_x + \beta_z \Delta y}{h_{\text{WL}}}, \quad (3)$$

where Δx and Δy are the horizontal and vertical offsets between the centroids of the two ROIs, h_{WL} is the weak layer thickness, and β_z is the mean rotation in radians to account for relative rotation between the two ROIs. The mean rotation β_z was used to correct the displacement differences following Schreier and others (2009).

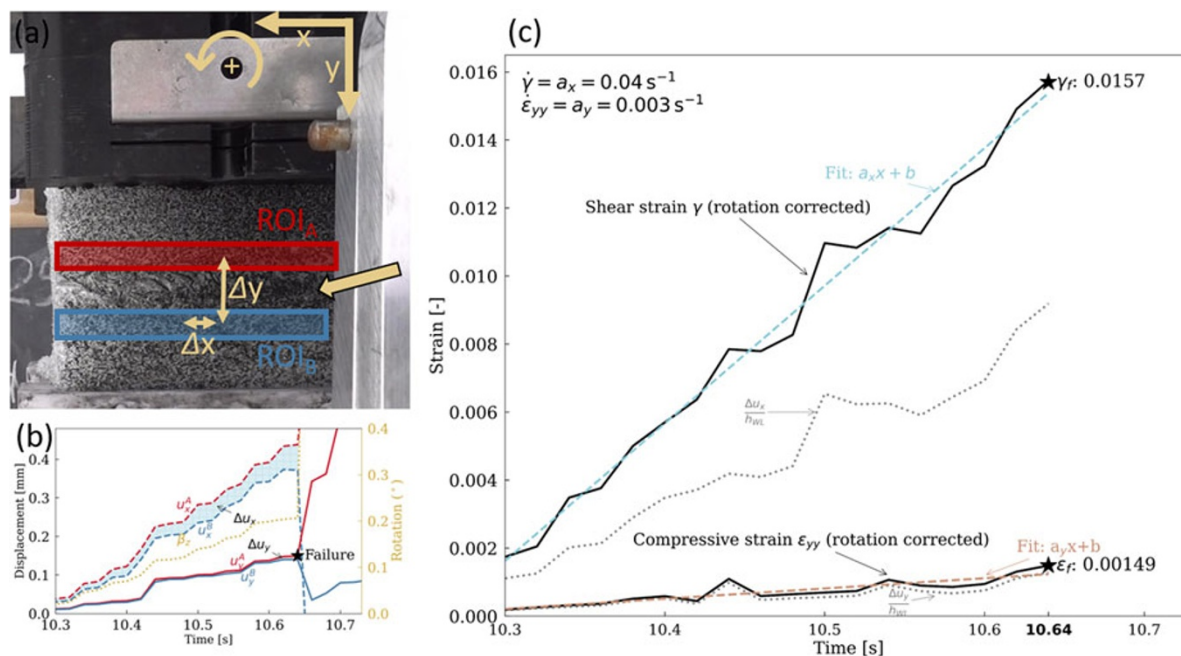


Figure 3. (a) For the DIC analysis, two regions of interest (ROIs) were selected, one above the weak layer (ROI_A, in red) and one below the weak layer (ROI_B, in blue). In the experiment shown (SH25-1332), the loading direction was 15° with the horizontal axis (see yellow arrow). The coordinate system is displayed in the top right, with the rotation being positive in the counterclockwise direction. Δx and Δy are the horizontal and vertical offsets between the centroids of the two ROIs (out of scale). (b) The horizontal (u_x) and vertical displacement (u_y) of both ROIs, as well as the mean vertical rotation β_z in a time interval just before failure. The differences in the displacements of ROI_A and ROI_B, Δu_x and Δu_y , are the effective displacements in the weak layer. (c) The relative displacements $\Delta u_x/h_{WL}$ and $\Delta u_y/h_{WL}$ are then corrected for the rotation following Eqn (3), resulting in the shear strain and compressive strain with $\gamma_f = 1.6 \times 10^{-2}$ and $\epsilon_f = 1.5 \times 10^{-3}$ being the rotation-corrected strain values just before failure at $t = 10.64$ s. The coefficients a_x and a_y of the linear fits on the corrected strain are the strain rates in the weak layer: $\dot{\gamma}_{xy} = 4 \times 10^{-2} \text{ s}^{-1}$ and $\dot{\epsilon}_{yy} = 3 \times 10^{-3} \text{ s}^{-1}$ in this example.

and the procedure described by Schöttner and others (2026). By applying a linear fit to the strain values in the selected interval right before failure, strain rates were determined as the slope coefficients of the strain–time fits (Fig. 3c). Details on the strain calculation are given in Appendix Fig. A2 and Table A1.

3. Results

3.1. Snowpack and weak layer characterization

The SH24 weak layer formed around 25 December 2023, had a thickness of approximately 1 cm and was buried about 40 cm below the snow surface at the time of testing (Fig. 4a). In some samples, ice from flow channels was present within the weak layer due to rainfall in January 2024. Samples with obvious ice formations visible in the field were discarded. In our experiments, the slab above the weak layer was approximately 5 cm thick and consisted mainly of rounding faceted particles (FCxr). The SH25 weak layer formed around 22 January 2025, had a similar thickness of approximately 1 cm and was also buried at a depth of about 40 cm below the surface (Fig. 4b). The slab above this layer consisted predominantly of faceted crystals.

Microstructural parameters derived from μ CT analysis of one sample each of the two weak layers are summarized in Table 2. Detailed microstructural images are given in the Appendix (Fig. A1). While weak layer densities were nearly identical for both layers, the SSA and connectivity density were higher in 2025 than in 2024 by approximately 28% and 63%, respectively. Mean local pore and ice thicknesses were lower in 2025 by approximately 24%, indicating a finer and more connected microstructure. The mean curvature H was 5 times higher for SH25 than for

SH24. Geometrically, this indicates stronger convex shapes and thus rounder structures. At the same time, the Gaussian curvature K had a smaller negative value for SH25 by approximately 40%, which geometrically means less pronounced saddle-shaped structures in SH25.

3.2. FE results

FE simulations were used to assess the effective stress state within the weak layer resulting from the imposed loading conditions. Those simulations provided a range of uncertainties for the effective loading angles (see Appendix Fig. A4 for details), which were subsequently used for stress decomposition in the failure envelope analysis. Figure 5 shows exemplary stress distributions in the sample from the FE simulations under load boundary conditions and DBCs. Qualitatively, the stress distributions under compressive or shear loading (Fig. 5a and d, c and f) appear similar for FBCs and DBCs. In contrast, the stress distributions under mixed mode (45°) loading (Fig. 5b and e) exhibit greater differences between FBCs and DBCs.

3.3. Strain rates during loading

Effective weak layer strain rates across the weak layer were estimated from video recordings using DIC for a subset of experiments (Section 2.5): 13 videos for SH24 and 51 videos for SH25. For SH24, the median effective shear and compressive strain rates in the weak layer immediately before failure were on the order of 10^{-3} s^{-1} with their interquartile range spanning a maximum of one order of magnitude and thus being on the same order of magnitude as the nominal strain rate in the entire specimen (10^{-3} s^{-1}). For

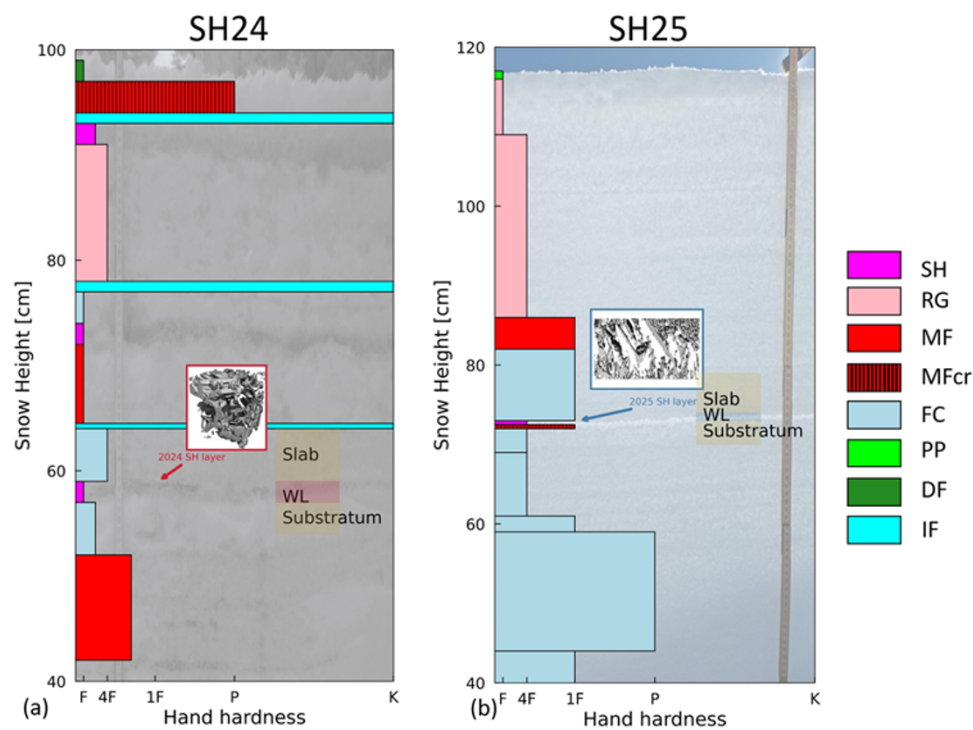


Figure 4. (a) Snow profile for SH24, with a 3-D image of the μ CT scan of the surface hoar weak layer in the red box. (b) Snow profile for SH25, with a 2-D image of the surface hoar weak layer in the blue box. Grain types are colored following Fierz and others (2009).

Table 2. Microstructural properties of SH24 and SH25: weak layer density ρ_{WL} , specific surface area SSA, vertical anisotropy calculated from exponential correlation lengths α_z , connectivity density C_v , mean local pore thickness $\bar{t}_{pore}$ and mean local ice thickness $\bar{t}_{ice}$, mean horizontal tortuosity $\bar{\tau}^{xy}$ and vertical tortuosity τ^z , mean interface curvature H and Gaussian interface curvature K .

	ρ_{WL} (kg m ⁻³)	SSA (mm ⁻¹)	α_z (-)	C_v (mm ⁻³)	$\bar{t}_{pore}$ (mm)	$\bar{t}_{ice}$ (mm)	$\bar{\tau}^{xy}$ (-)	τ^z (-)	H (mm ⁻¹)	K (mm ⁻²)
SH24	154	7.60	1.02	0.51	0.41 ± 0.19	1.75 ± 0.87	2.13	1.76	0.58	-26.18
SH25	152	9.76	0.96	0.83	0.31 ± 0.12	1.33 ± 0.67	1.86	1.81	2.53	-15.82

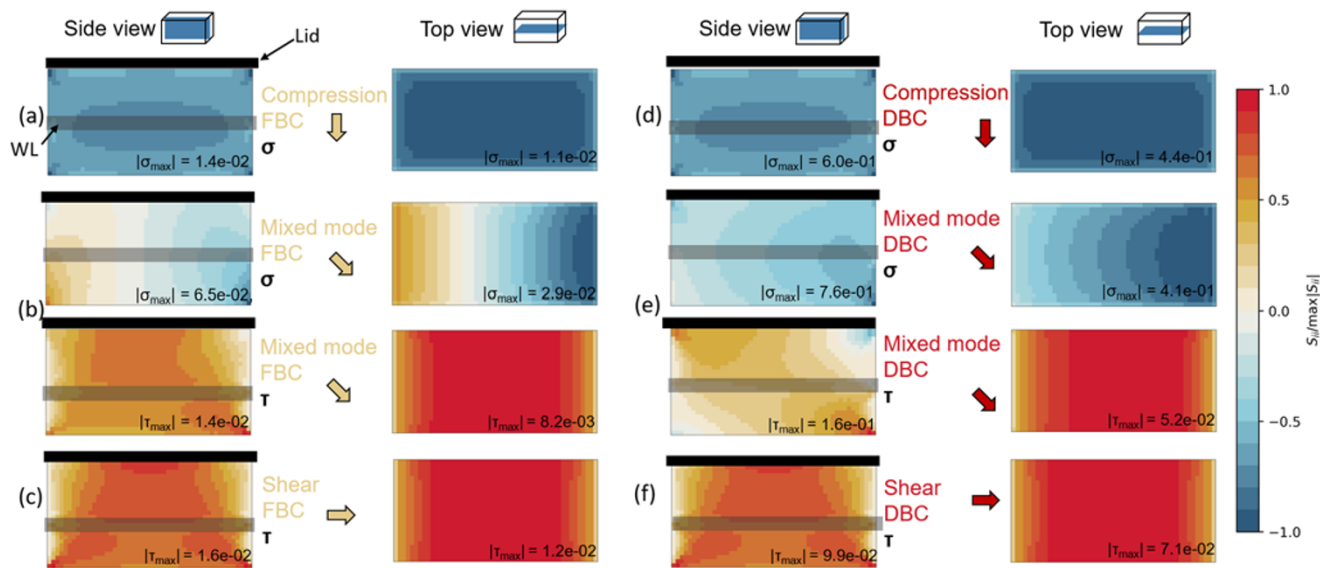


Figure 5. Exemplary stress distribution of the finite element simulations of a three-layer snow block under force boundary conditions (FBCs) (a–c) and displacement boundary conditions (DBC) (d–f), with a side view in the middle of the sample and a top view at the height of the weak layer next to each other. (a) and (d) show the compressive stress σ under compressive loading ($\alpha = 90^\circ$). In (b) and (e), both the compressive stress σ (top figure) as well as the shear stress τ (bottom figure) are shown for mixed mode loading ($\alpha = 45^\circ$). In (c) and (f), shear stress τ is shown under shear loading ($\alpha = 0^\circ$). In all shown simulations, $\nu = 0.3$ for all layers, $E_{base}:E_{wl}:E_{slab} = 5:1:5$, lid tilting = 0 and the load distribution is equal. The deformations of the samples are scaled by a factor of 8 for visibility. All stresses were normalized by the absolute maximum stress value, as indicated in each stress field. The color bar shows the normalized stress $S_{ij}/\max|S_{ij}|$, referring to either σ or τ .

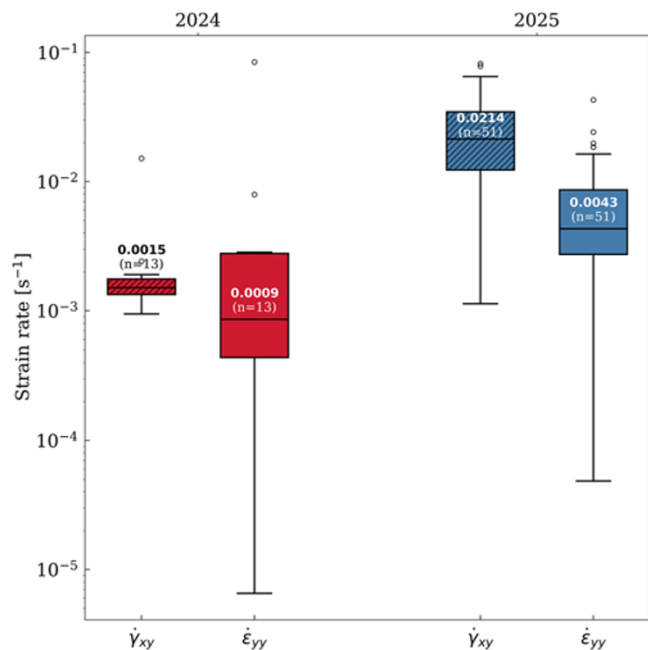


Figure 6. Boxplots of the effective strain rates in the weak layer, identified from the video recordings using digital image correlation, where $\dot{\gamma}_{xy}$ is the shear strain rate and $\dot{\epsilon}_{yy}$ is the compressive strain rate. The central line in each box is the median, with the corresponding median values printed just above. The box bounds are the 25th and 75th percentiles (interquartile range, IQR), the whiskers indicate the spread within $1.5 \times \text{IQR}$, and the open circles denote outliers beyond this range. Values for SH24 are in red ($N = 13$) and for SH25 in blue ($N = 51$).

SH25, the median values of the effective compressive and shear strain rates were on the order of 10^{-3} s^{-1} and 10^{-2} s^{-1} , respectively (Fig. 6). The effective shear strain rate in the weak layer was again on the same order of magnitude as the nominal strain rate in the whole sample (10^{-2} s^{-1}), and the compressive strain rate was slightly lower.

3.4. Failure envelopes

We performed 54 experiments for SH24 and 88 for SH25. After applying the quality criteria described in Section 2.3, 43 experiments of SH24 and 75 of SH25 were retained to determine the failure envelopes (Fig. 7). Because the experiments were performed at a discrete set of loading angles, the stress data naturally cluster along distinct directions in stress space. The scatter along these directions reflects the variability in failure force for a given loading angle. For both datasets, using the nominal loading angle, an elliptical failure envelope captured the overall trend of the stress states at failure reasonably well. However, the reduced chi-squared values $\chi^2_\nu \gg 1$ indicate substantial scatter relative to the estimated uncertainties. For SH24, the fitted strengths were $\sigma_c^{\text{SH24}} = 7.9 \pm 0.6 \text{ kPa}$ and $\tau_c^{\text{SH24}} = 5.8 \pm 0.4 \text{ kPa}$ ($\chi^2_\nu = 13.8$). For SH25, the fitted strengths are $\sigma_c^{\text{SH25}} = 5.0 \pm 0.3 \text{ kPa}$ and $\tau_c^{\text{SH25}} = 3.5 \pm 0.2 \text{ kPa}$ ($\chi^2_\nu = 12.0$). Both compressive and shear strength were thus higher for SH24, with σ_c^{SH24} exceeding σ_c^{SH25} by approximately 58% and τ_c^{SH24} exceeding τ_c^{SH25} by approximately 65%. For both SH24 and SH25, the fitted envelope for the FBC data was very similar to the fit using the raw stress data. In contrast, the fitted envelope for the DBC data yielded lower strength values but still lay within the 95% confidence interval of the raw fit.

4. Discussion

In this study, we performed experiments on two weak layers of buried surface hoar under multiaxial loading conditions in the field. Using a custom-designed MSCU, we derived failure envelopes describing combined compressive–shear strength. The experiments demonstrate the feasibility of multiaxial testing under natural snowpack conditions and provide apparent strength envelopes for two natural weak layers. Regarding the tested weak layers, compressive strength exceeded shear strength in both datasets, and both strength components were higher for the layer SH24 than for SH25.

4.1. Methodological limitations and uncertainties

Although the custom-designed testing machine was well-suited for field measurements, our results highlight several methodological limitations and sources of uncertainty.

A central limitation arises from the compliance of the overall loading system. While the MSCU is designed to impose a prescribed displacement rate at the actuator, video recordings showed that significant tilting occurred outside the weak layer, and the weak layer was therefore not perfectly loaded in displacement control. DIC revealed that the effective strain rate across the weak layer was on the same order of magnitude as the applied nominal strain rate in the whole sample. Moreover, the effective weak layer strain rates varied not only among loading angles but also within a given loading angle, reflecting natural variability of the surrounding snow slabs and the exact settling and alignment of each sample in the machine. This implies that there was no strain concentration in the weak layer and suggests that, despite higher stiffness of the surrounding slab and base layers, additional effects caused larger strains in the slab and the weak layer. Altogether, this indicates that the effective deformation of the weak layer is not directly controlled by the motor speed but by the compliance of the loading system and the surrounding snow. Deformation and progressive damage of the snow in the slab and in the substratum surrounding the inlays likely absorb a large fraction of the imposed displacement before stress is efficiently transmitted to the weak layer.

The derived effective weak layer strain rates should thus be interpreted as a system response rather than a direct reflection of the imposed motor speed. In contrast, Schöttner and others (2025) performed laboratory experiments in which the top and bottom plates were frozen to the snow sample, resulting in much stronger coupling and substantially lower system compliance. Under these conditions, the applied displacement rate was transmitted more directly to the weak layer. The field-based nature of the present experiments, therefore, inherently limits strain-rate control compared to laboratory setups. Nevertheless, the derived effective weak layer strain rates indicate that the testing still occurred fast enough to be in the brittle regime, i.e. without substantial softening before failure ((Schweizer, 1998)).

An additional source of uncertainty concerns the effective loading direction. While the substratum was generally well constrained in the sample holder, the slab–lid interface exhibited noticeable tilting despite the use of stabilizing clamps. Such tilting affects both the effective loading angle and the stress distribution within the weak layer. FE simulations partly account for these effects by modeling tilting of the lid and uneven load distributions. We therefore interpret the mixed-mode data using effective loading angles, rather than relying solely on the nominal loading angle. Yet

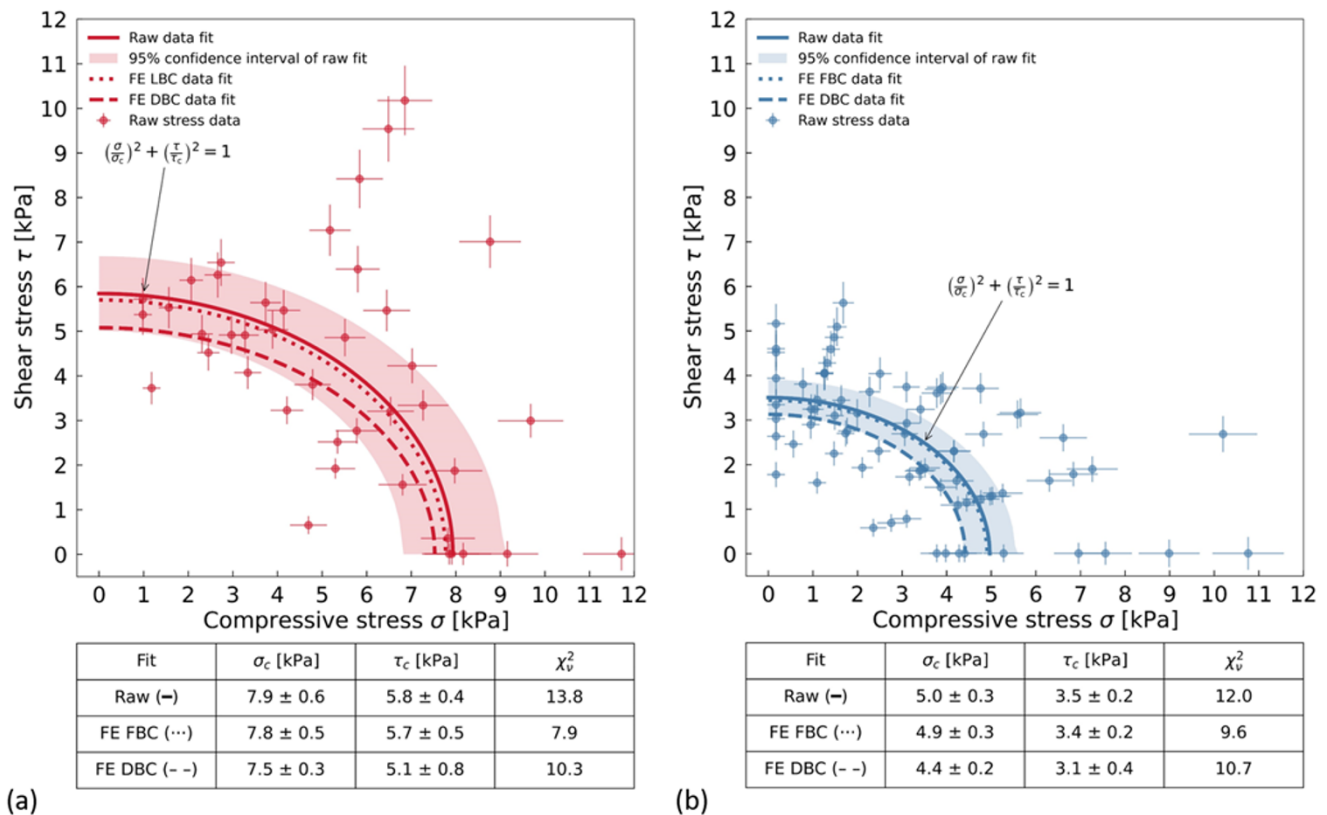


Figure 7. (a) Failure envelope for SH24 ($N = 43$) and (b) for SH25 ($N = 75$). The solid line shows the orthogonal distance regression fit to the raw stress data, accounting for a loading angle uncertainty of $\pm 2^\circ$, together with its 95% confidence interval. The dashed and dotted lines represent fits to data modified using the effective loading angle obtained from finite-element (FE) displacement boundary conditions (DBCs) and force boundary conditions (FBCs), respectively. For the sake of clarity, the confidence intervals for fits with the effective loading angles are not shown.

future improvements to the testing machine should aim to further constrain rotational degrees of freedom, for example, by using a clamped ball joint on the lid.

Moreover, differences in boundary conditions between the two field campaigns should be considered. The heavier lid used in 2024 increased the compressive contribution to the stress state, highlighting the sensitivity of multiaxial weak layer testing to system compliance and boundary conditions. Although the 2025 campaign incorporated several improvements to the testing machine, including a lighter lid and a substantially faster actuator, the scatter in the measured strengths remained comparable to that of the 2024 campaign. This indicates that the dominant sources of experimental uncertainty are unlikely to be the actuator speed or the dead load of the lid alone, but rather the compliance of the snow-machine system, local load transfer, and the inherent heterogeneity of the snow sample. The improvements introduced in 2025 nevertheless reduced the systematic compressive bias associated with the heavier lid and therefore simplified the interpretation of the imposed loading conditions. A further limitation is that only a single specimen geometry was tested, so size and edge effects were not evaluated and the transferability of the reported strengths and failure envelope to other specimen sizes remains unknown.

Taken together, these limitations imply that the reported strength data should be interpreted as setup-dependent apparent strength values rather than intrinsic material properties of weak snow layers. Compression-dominated experiments are mechanically simpler to interpret because the load path is more direct

and less sensitive to imperfect coupling between the sample, lid, and holder. However, the scatter in the compression-dominated measurements is comparable to that observed under mixed-mode loading, indicating that uncertainties associated with the loading path are not the only source of variability. Instead, the remaining scatter likely reflects a combination of natural weak-layer heterogeneity, local load transfer, and experimental boundary effects. Consequently, while mixed-mode and shear-dominated experiments should be interpreted with greater caution because of their increased sensitivity to lid tilting and system compliance, we believe that the reported strengths provide the correct order of magnitude for the multiaxial strength of the investigated weak layers, and that the relative differences between loading conditions and between the two weak layers are more robust than the absolute values. Direct quantitative comparison with tightly coupled laboratory experiments (e.g. Schöttner and others, 2025; 2026) or between different experimental setups should be made with caution. Despite these limitations, the experiments consistently demonstrate that weak-layer failure is governed by the combined action of compressive and shear stresses, and the derived failure envelopes provide a useful description of the observed mixed-mode failure behavior.

4.2. Failure behavior and shape of the failure envelope

The measured failure stresses showed a coupled dependence on compressive and shear stress and, despite substantial scatter, were reasonably described by the assumed elliptical failure envelope.

This supports the interpretation of weak layer failure as a mixed-mode process, consistent with previous laboratory and numerical studies (e.g. Reiweiger and Schweizer, 2010; Chandel, 2014; Schöttner and others, 2026).

We also explored alternative failure criteria, including capped Mohr–Coulomb formulations (Reiweiger and others, 2015). Such models can yield lower reduced chi-squared values, yet mostly due to their higher number of fit parameters. Our data suggest that the Mohr–Coulomb model is not an appropriate fit. In particular, for the 2024 dataset, the fitted capped Mohr–Coulomb model resulted in unrealistically low shear strength values of <1 kPa that are not supported by the observed stress data. Given the absence of tensile stress data and the sensitivity of multi-parameter models to limited and scattered datasets, we therefore refrain from interpreting capped Mohr–Coulomb fits further. In this context, the elliptical envelope is favored for its descriptive simplicity and robustness rather than statistical optimality.

We observed a higher shear strength in the present study compared to Schöttner and others (2026), who also investigated the layer SH24 under laboratory conditions. This observed difference in strength is most likely related to differences in loading configuration. While the compressive strengths are very similar (7.8 kPa versus 7.9 ± 0.6 kPa), the shear strength reported by Schöttner and others (2026) (2.2 kPa) is lower than the value obtained here (5.8 ± 0.4 kPa). A key difference is that the present dataset does not include experiments in pure simple shear. In the 2024 configuration, the combined weight of the lid and the loading frame always introduced a compressive component, such that no data points lie close to the pure-shear axis. This limits the direct comparability of shear-dominated strength values and may bias the inferred shear strength toward higher values. Schöttner and others (2026) reported strain rates on the order of 10^{-3} s^{-1} , similar to the effective strain rates in the present experiments. Particularly, the very similar shear strain rates cannot explain the observed difference in shear strength. Given the absence of pure simple shear data and the systematic compressive bias from the lid, we attribute the higher apparent shear strength primarily to differences in effective loading direction and boundary conditions, rather than to an intrinsic increase in material shear strength. The compressive strength agreement and the relative envelope shape are therefore more informative for comparison than the absolute values of shear strength.

Although differences in strength are observed within SH24 and SH25, the available auxiliary data suggest that strain rate does not exert a systematic influence on the measured strength values. Any apparent decrease in strength at higher strain rates remains ambiguous due to substantial scatter in the measurements (Appendix Fig. A6). Similarly, no consistent trend with time of day (and indirectly—snow temperature) was observed (Appendix Fig. A5). Most plausibly, the potential experimental artifacts associated with the MSCU and its boundary conditions may have contributed to the observed differences between the data points. The substantial scatter of the data points likely reflects both natural heterogeneity of the snowpack as well as experimental boundary condition effects. With our current methodological approach, we cannot isolate the effect of natural weak layer heterogeneity. The sensitivity of the stress state to lid mass, tilting and load transfer suggests that setup-induced effects are an important source of variability, while the natural heterogeneity of the snowpack might also add to the variability of the data. Moreover, variability in the slab density might have influenced the effective strain rate and the observed strength values.

4.3. Microstructural interpretation and implications

The observed strength differences between the two datasets may partly reflect differences in weak layer microstructure, although this interpretation remains qualitative. Recent studies have identified pore geometry, ice thickness and connectivity density as key parameters controlling snow mechanical behavior (Schöttner and others, 2026). In the present study, SH24 exhibited lower SSA and connectivity density but larger local ice thickness compared to SH25 (Table 2). Such differences of the microstructure could lead to different deformation mechanisms on the microscale, potentially resulting in higher apparent strength values. Moreover, SH25 had a larger positive mean curvature H and a smaller negative Gaussian curvature K , potentially hinting at thinner structures that are more prone to buckling. However, we analyzed only one μCT sample per dataset ($n = 1$ for SH24 and SH25). Absolute differences between these scans are therefore descriptive only and do not permit a statistical assessment of microstructural differences. For this reason, we cannot attribute the strength contrast to the differences in microstructure; geometric effects, boundary conditions and experimental uncertainties remain equally plausible explanations.

5. Conclusion

We developed a mobile shear–compression test unit to investigate the multiaxial strength of weak snowpack layers under controlled loading conditions in the field. Applying this mixed-mode loading apparatus, we measured the strength of two weak layers of buried surface hoar for various loading angles in the field and derived the corresponding failure envelopes. The observed failure behavior showed a coupled contribution of compressive and shear stresses to the failure of the weak layer and was described reasonably well by an elliptical envelope curve. The strength of the 2024 weak layer was consistently higher than that of the 2025 weak layer. For both layers, the compressive strength exceeded the shear strength. The results reinforce that weak layer failure cannot be described by a single scalar strength value but depends on the combined stress state.

The effective stress state within the weak layer differed from the applied boundary conditions. Video-based analyses revealed that a large fraction of the imposed displacement was absorbed by deformation and damage in the loading system and the surrounding snow. Together with the FE simulations, these findings suggest that the measurements are influenced by system compliance. This highlights the need for caution when comparing strength values obtained using different experimental setups or when directly comparing field-based and laboratory measurements. The data should be interpreted in the context of the experimental boundary conditions and loading constraints.

Despite these limitations, the presented approach enables measuring the strength of natural weak layers under mixed-mode loading conditions. In the field, many data points can be collected, which is difficult to reproduce in laboratory settings. The suggested failure envelopes provide useful constraints on the shape and order of magnitude of mixed-mode failure under field boundary conditions, for informing numerical models of slab–weak layer interaction, while absolute strength values should be treated with the uncertainties reported. Future work should aim to reduce system compliance and expand testing to additional weak layer types to better constrain the role of strain rate and microstructure in governing weak layer failure.

Data availability statement. Details on the mobile shear–compression unit (MSCU) and the dataset are available on EnviDat at <https://doi.org/10.16904/envi.dat.794>.

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Appendix

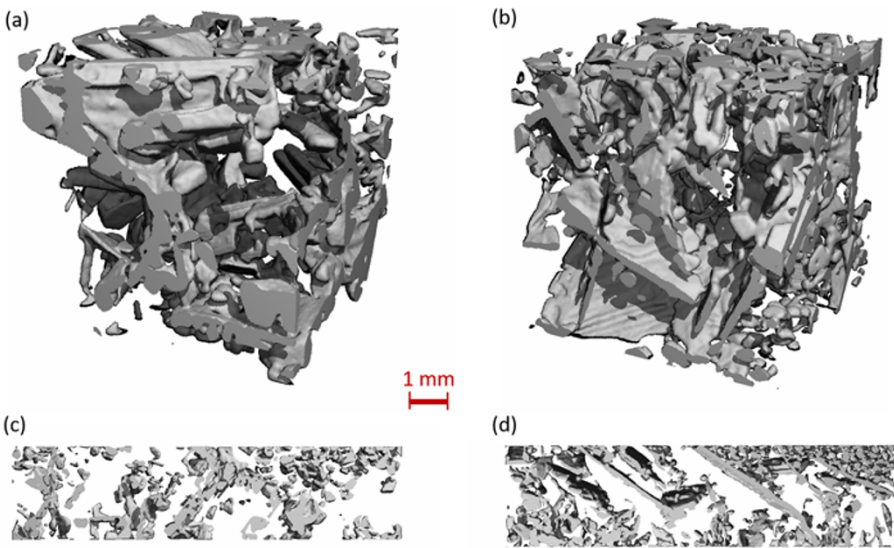


Figure A1. Three-dimensional images of the microstructure of the weak layers SH24 (a) and SH25 (b) and in two dimensions in (c) and (d).

Table A1. Details of strain rate calculation of the example in Figure 3.

Symbol	Description	Value
h_{WL}	Weak layer thickness	7.2 mm
β_z	Mean rotation	0.2 ° (*)
$\Delta u_x/h_{WL}$	Relative horizontal displacement in WL	0.0092 (*)
$\Delta u_y/h_{WL}$	Relative vertical displacement in WL	0.0013 (*)
Δx	Horizontal offset between centroids of ROI _A and ROI _B	0.4 mm
Δy	Vertical offset between centroids of ROI _A and ROI _B	13.1 mm
$(\beta_z \Delta x)/h_{WL}$	Rotation correction for shear strain	0.0002
$(\beta_z \Delta y)/h_{WL}$	Rotation correction for compressive strain	0.0066
γ_{xy}	Shear strain (corrected for rotation)	0.016 (*)
ε_{yy}	Compressive strain (corrected for rotation)	0.0015 (*)
$\dot{\gamma}$	Shear strain rate (corrected for rotation) from fit (a_x)	0.04 s ⁻¹
$\dot{\varepsilon}_{yy}$	Compressive strain rate (corrected for rotation) from fit (a_y)	0.003 s ⁻¹

Note: Values marked with (*) represent the value just before failure.

Figure A2. Strain rate calculation from the example in Figure 3, with the explicit formulae for the rotation-corrected strain rates as described in Section 2.5. Strain is on the vertical axis and time on the horizontal axis. Dotted lines are the vertical and horizontal strains, solid lines are the strains corrected for rotations. The dashed blue line is the linear fit to the horizontal strain, with a_x representing the compressive strain rate. Similarly, the dashed beige line is the linear fit to the vertical strain, with a_y representing the shear strain rate.

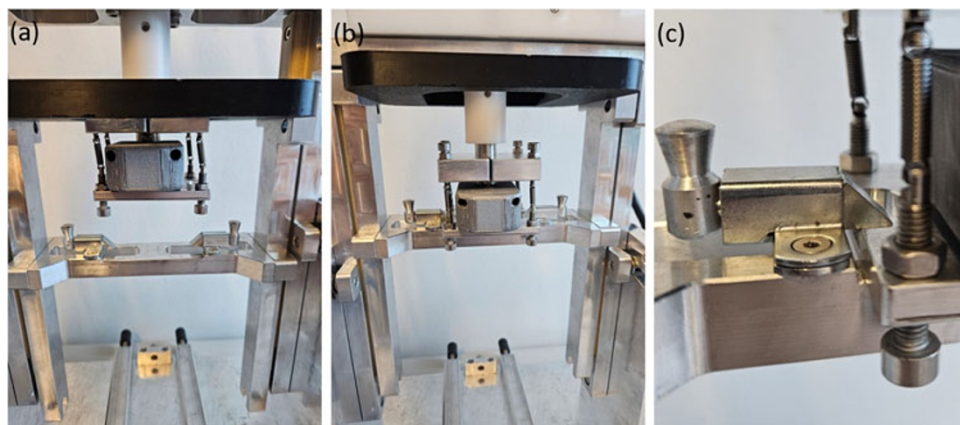
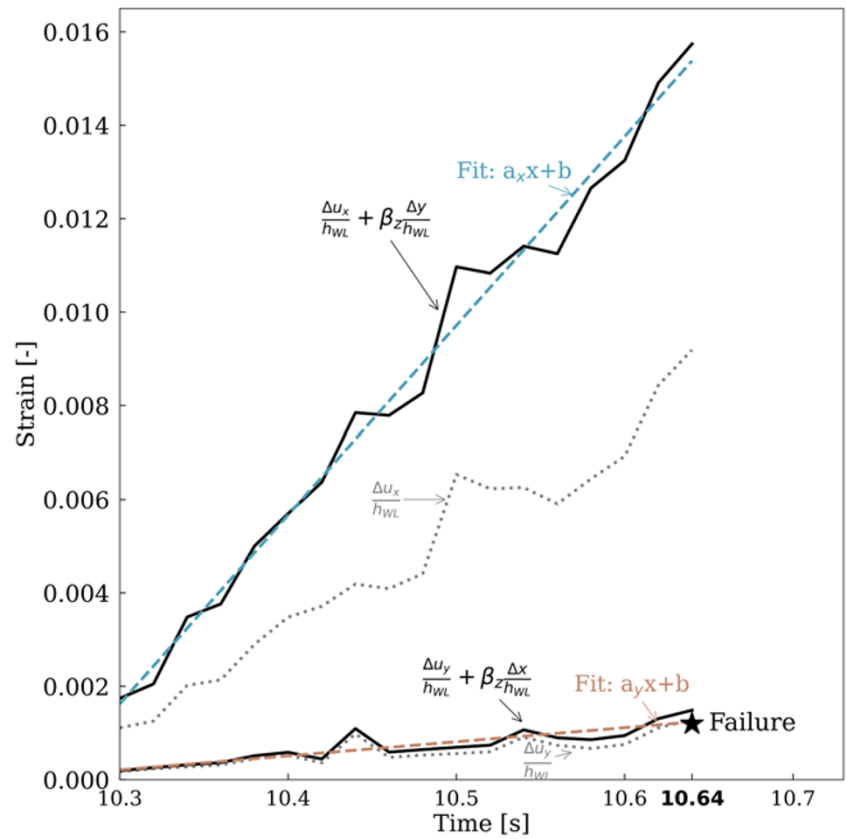


Figure A3. Details on the spring system in the MSCU, added for SH25, where the springs are carrying the lifting frame. (a) Disconnected, (b) connected and (c) close-up of the clipping system.

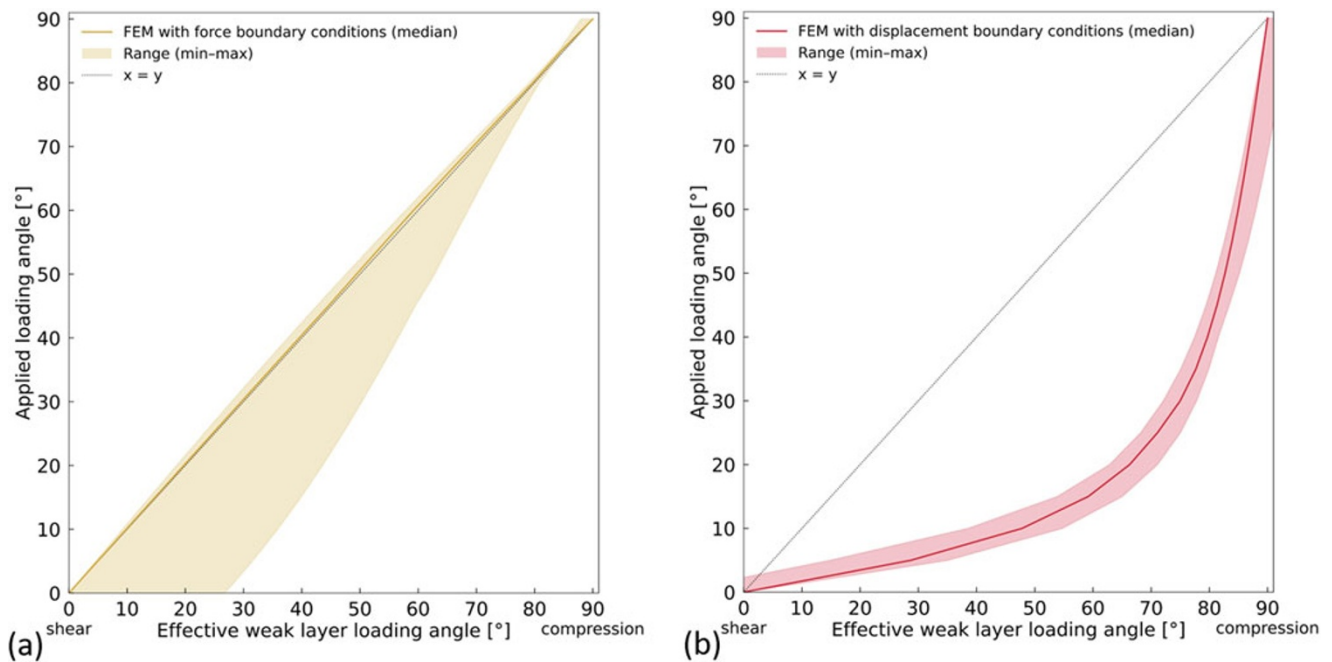


Figure A4. Finite element analysis: The applied loading angle versus the effective loading angle, where the angle is measured against the horizontal axis (0° = shear, 90° = compression). Parameter studies varied the Poisson's ratios ν of weak layer and slab (0.1, 0.2, 0.3, 0.4), the ratio between the elastic modulus of weak layer and slab (and base) ($E_{WL} : E_{slab}$, 1:2, 1:5, 1:10), the lid orientation (either aligned with the sample surface, $\beta_{lid}=0^\circ$, or tilted by 2° around the x -axis and the load distributions (equally on the two pins: ld 100/100, unequally on the two pins: ld 110/100). (a) FE simulation with force boundary conditions. (b) FE simulation with displacement boundary conditions.

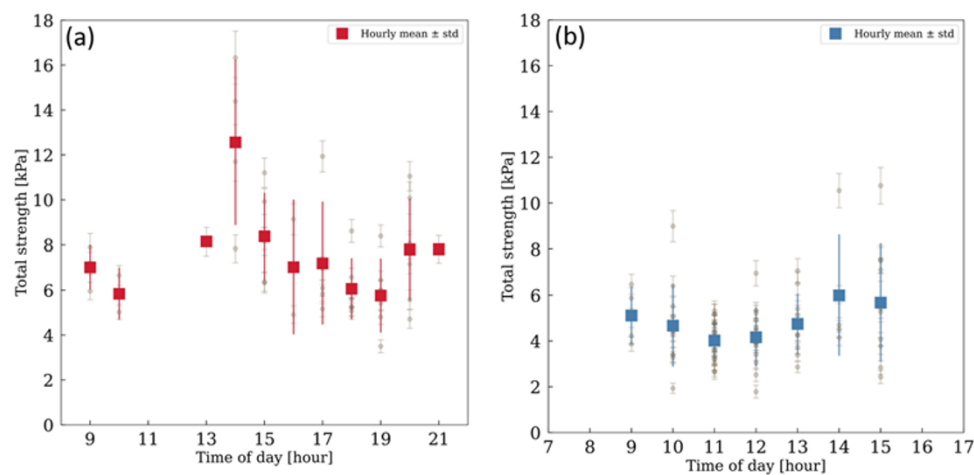


Figure A5. Total strength versus time of day for (a) SH24 and (b) SH25. Note that in 2024, some data points were collected in the evening with no daylight.

