

TOWARDS A MICROSTRUCTURE-INFORMED REPRESENTATION OF STRENGTH AND STIFFNESS OF WEAK SNOW LAYERS

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ABSTRACT: Compilations of the mechanical properties of snow often exhibit scatter spanning orders of magnitude. The resulting uncertainty poses a significant challenge for the deterministic modeling of physical processes such as avalanche release. Much of this variability is due to differences in snow microstructure, so that density alone provides an incomplete description of mechanical behavior. This limitation is especially critical for weak layers where extreme microstructural configurations are prevalent. To bridge this gap, we collected and analyzed a comprehensive dataset of approximately 300 uniaxial compression experiments complemented by 70 co-located micro-computed tomography (μ CT) scans. We show that much of the systematic variation can be captured by employing simple power laws that depend on grain type. This approach provides a practical solution for implementation in current snow cover models. Furthermore, statistical analysis revealed specific microstructural features associated with the mechanical behavior of weak layers. The effective elastic modulus was primarily related to internal orientation and the efficiency of load paths through the material, which are captured by parameters such as anisotropy and tortuosity. Strength correlates with parameters such as surface curvature and tortuosity. Finally, differences in how strength and stiffness scale with density suggest distinct deformation regimes. We find that persistent weak layers show behavior comparable to microstructures dominated by stretching, while decomposing particles and rounded grains show behavior closer to bending-dominated structures. This finding provides a representation in which density does not appear explicitly and aids in developing numerical and analytical simplifications to capture the response of complex microstructures in simplified macroscopic representations.

KEYWORDS: snow slab avalanches, snow mechanics, weak layers, microstructure, strength, stiffness

1. INTRODUCTION

Dry-snow slab avalanches release when a buried weak layer loses its load-bearing capacity which can result in a crack propagating beneath the overlying cohesive slab (e.g. Schweizer et al. 2016). Mechanical models of this process require, among other inputs, representative values for weak layer stiffness and strength (Rosendahl and Weißgraeber 2020). However, compilations of snow mechanical properties show scatter spanning orders of magnitude, even among samples with similar density (e.g. Mellor 1975; Shapiro et al. 1997). This uncertainty limits the predictive capability of mechanical avalanche-release models and is particularly relevant for thin weak layers, which can exhibit heterogeneous and highly anisotropic microstructures (e.g. Walters and Adams 2014).

Snow density is widely used to parameterize mechanical properties because it is relatively straightforward to measure. As in many porous materials,

density provides a useful first-order measure of the amount of load-bearing solid material. It does not, however, describe how this material is arranged. Snow samples with equal density can differ substantially in the orientation, connectivity and geometry of their bonded ice skeletons, resulting in different load paths and stress distribution (e.g. Schöttner et al. 2026b). Consequently, a single density-based relation cannot be expected to represent mechanical behavior across the full range of snow microstructures. Persistent weak layers composed of faceted crystals, depth hoar or buried surface hoar are especially relevant in this context, as their structures differ strongly from those formed by decomposing particles and rounded grains.

Micro-computed tomography (μ CT) resolves the three-dimensional ice network, which allows to characterize microstructure quantitatively (Köchle and Schneebeli 2014). Parameters such as anisotropy, tortuosity and surface curvature describe different aspects of the microstructure that may influence its mechanical response (e.g. Roberts and Garboczi 2002). Directly resolving these structures in snow cover or slope-scale models is neither practical nor operationally feasible.

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Applications therefore require a reduced representation of the microstructural complexity that preserves its dominant mechanical effects while relying on variables available in current snow cover models.

We synthesize previously published results from about 300 uniaxial compression experiments and 70 co-located μ CT scans covering faceted crystals and depth hoar, buried surface hoar, and decomposing particles and rounded grains (Schöttner et al. 2026b). Based on these results, we present two practical ways to represent microstructural effects in mechanical and snow cover models. First, grain type-dependent power laws describe the density dependence of effective elastic modulus and compressive strength. Second, the relation between stiffness and strength provides a simplified framework for distinguishing dominant deformation regimes. We illustrate the practical use of these representations with an application in SNOWPACK (Bartelt and Lehning 2002).

2. DATA AND METHODS

We compiled a dataset of uniaxial compression experiments covering three groups of snow microstructures: faceted crystals and depth hoar (FC/DH; $N = 114$), decomposing particles and rounded grains (DF/RG; $N = 132$), and buried surface hoar (SH; $N = 53$). FC/DH and DF/RG layers were produced in the cold laboratory to obtain a broad and controlled range of densities and microstructures. FC/DH layers were grown by temperature-gradient metamorphism, whereas DF/RG layers were prepared by sieving snow between denser slab layers and allowing them to sinter. As buried surface hoar could not be reliably produced in the lab, natural SH layers were sampled in the Flüela Valley near Davos, Switzerland. All specimens consisted of a weak layer embedded between two denser snow layers. This configuration protected the fragile weak layer during handling and provided an interface for mechanical testing. The complete procedures for sample preparation and testing are described in (Schöttner et al. 2026b; Schöttner et al. 2025a).

Compression experiments were performed with a displacement-controlled uniaxial testing machine. The strain in the weak layer was determined from high-speed recordings using digital image correlation (DIC). For this purpose, the relative vertical displacement between regions immediately above and below the weak layer was divided by their initial distance. This isolated weak layer deformation from the compliance of the surrounding slab layers

and the sample–machine interfaces. The mean effective strain rate was $2.1(\pm 0.9) \times 10^{-3} \text{ s}^{-1}$, with comparable values among the three grain type groups. Compressive strength, σ_c , was defined as the maximum stress before the abrupt stress drop associated with weak layer failure. The effective elastic modulus, E , was obtained from linear segments of the synchronized stress–strain curves. Usable stress–strain records were obtained for 241 specimens.

The three-dimensional microstructure of each parent sample was characterized using micro-computed tomography (μ CT). In total, 70 co-located scans were acquired at voxel sizes between 16.2 and 29.1 μm . After filtering and segmentation into ice and pore space, a cubic region containing only the weak layer was selected. From this volume, we calculated 44 bulk descriptors, including specific surface area, anisotropy, correlation and chord lengths, connectivity measures, tortuosity, and surface curvature. The μ CT volume and the mechanically tested specimens originated from the same parent sample but generally did not correspond to identical physical specimens. We excluded descriptors requiring grain segmentation because such segmentation was not feasible for all samples and, for some of the investigated microstructures, a grain-based representation is not physically meaningful.

To obtain practical parameterizations, the mechanical properties were related to ice volume fraction,

$$\phi = \frac{\rho}{\rho_{\text{ice}}}, \quad (1)$$

where $\rho_{\text{ice}} = 916.7 \text{ kg m}^{-3}$ is the density of ice. The mechanical properties were then related to ϕ using grain-type-dependent power laws,

$$\frac{E}{E_{\text{ice}}} = A_E \phi^{b_E}, \quad (2)$$

and

$$\frac{\sigma_c}{\sigma_{\text{ice}}} = A_\sigma \phi^{b_\sigma}, \quad (3)$$

Here, $E_{\text{ice}} = 10 \text{ GPa}$ and $\sigma_{\text{ice}} = 2 \text{ MPa}$ are reference values used to normalize stiffness and strength, respectively (Nanthikesan and Sunder 1994; Petrovic 2003). The grain type-dependent coefficients and exponents were determined using orthogonal distance regression, accounting for uncertainties in both the mechanical properties and the ice volume fraction.

To identify the microstructural features associated with stiffness and strength, a neural-network model

was trained using the μ CT descriptors. Highly correlated descriptors were grouped using hierarchical clustering, and their influence was evaluated using repeated cross-validation and permutation importance. Full details of the statistical analysis are provided in (Schöttner et al. 2026b).

3. RESULTS AND DISCUSSION

3.1. Grain type-dependent scaling of stiffness and strength

Both the effective elastic modulus (or stiffness) and compressive strength increased strongly with ice volume fraction. However, the three grain type groups followed systematically different relations. Density therefore remained the dominant first-order predictor, but did not uniquely determine the mechanical response.

For the effective elastic modulus, FC/DH exhibited the strongest dependence on volume fraction, with a power-law exponent of $b_E = 5.1$. DF/RG showed a similarly steep exponent of $b_E = 4.6$, but generally had a lower modulus than FC/DH at comparable volume fractions. Buried SH followed a substantially shallower relation, with $b_E = 1.7$. The grain type dependence was also apparent for compressive strength. FC/DH showed a particularly steep increase with volume fraction, characterized by $b_\sigma = 5.7$. In comparison, DF/RG and SH had lower exponents of 2.8 and 2.1, respectively. The resulting power-law coefficients are summarized in Table 1.

The different power-law relations show that density alone does not provide a unique description of weak layer mechanics. At a given density, differences in the arrangement of the ice skeleton are reflected in systematically different stiffness and strength among the grain type groups. The relations in Table 1 provide a practical way to account for these differences using density and grain type, which are already represented in detailed snow cover models. Grain type should, however, be understood as a proxy for recurring microstructural configurations rather than as the fundamental mechanical variable. This approach therefore provides an intermediate representation between a single density-based relation and a fully microstructure-resolved mechanical model.

3.2. Microstructural influence on mechanical behavior

The microstructural analysis identified different groups of descriptors associated with stiffness and strength. The effective elastic modulus was most

Grain type	Property	A	b
FC/DH	E	1.8 ± 0.7	5.1 ± 0.3
	σ_c	19 ± 10	5.7 ± 0.4
SH	E	0.011 ± 0.009	1.7 ± 0.4
	σ_c	0.10 ± 0.10	2.1 ± 0.5
DF/RG	E	0.40 ± 0.30	4.6 ± 0.6
	σ_c	0.19 ± 0.10	2.8 ± 0.4

Table 1: Grain type-dependent power-law parameters obtained in Schöttner et al. 2026b for $E/E_{\text{ice}} = A_E \phi^{b_E}$ and $\sigma_c/\sigma_{\text{ice}} = A_\sigma \phi^{b_\sigma}$.

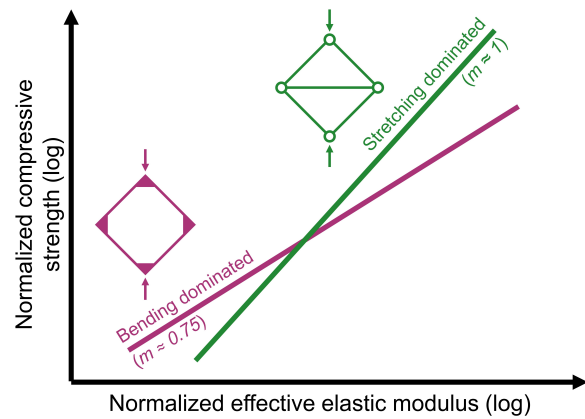


Figure 1: Schematic relationship between normalized compressive strength and effective elastic modulus for idealized cellular structures. On logarithmic axes, the corresponding power laws appear as straight lines, with different slopes (m) for stretching- and bending-dominated behavior. The fitted relations for FC/DH and SH are closer to the stretching-dominated regime, whereas DF/RG is closer to the bending-dominated regime.

strongly associated with anisotropies derived from the minimum cut density, followed by vertical tortuosity. Both parameters describe the alignment and efficiency of load-bearing paths and are therefore physically plausible predictors of stiffness.

For compressive strength, interfacial-curvature metrics and vertical tortuosity were the most important descriptors, although several other groups also showed relatively high importance. Curvature is unlikely to control strength directly, but may act as a proxy for the geometry of the bonding network. Vertical tortuosity characterizes the linearity of load paths, with more tortuous paths potentially promoting bending and stress concentrations. Since several descriptors showed grain type-dependent relationships, these global feature rankings should be interpreted with care.

3.3. *Stiffness–strength relation and deformation mechanisms*

Further insight was obtained by relating compressive strength directly to the effective elastic modulus. Combining the two power laws gives

$$\frac{\sigma_c}{\sigma_{ice}} = C \left(\frac{E}{E_{ice}} \right)^m, \quad m = \frac{b_\sigma}{b_E}, \quad (4)$$

where density no longer appears explicitly. The resulting exponents indicate two distinct effective regimes, illustrated schematically in Figure 1. FC/DH and SH yielded exponents of approximately 1.1 and 1.2, respectively, whereas DF/RG showed a lower exponent of approximately 0.6.

In idealized cellular solids, the relation between strength and stiffness was found to depend on the dominant microscale deformation mechanism. Stretching-dominated structures produce an approximately linear relationship, $m \approx 1$, whereas bending-dominated structures are expected to exhibit a lower exponent around $m \approx 0.75$ (Gibson and Ashby 1997; Ashby 2006). Within this idealized framework, the density-relation of FC/DH and SH is closer to stretching-dominated behavior, whereas DF/RG is more consistent with bending-dominated behavior.

This interpretation does not imply that deformation occurs exclusively through either stretching or bending. Snow contains irregular load-bearing structures, and deformation at the microscale likely involves a combination of stretching, bending, shear, rotation, and buckling. The fitted exponents instead describe the dominant effective response of the microstructure. Direct validation of these mechanisms would require deformation-resolving experiments or finite-element simulations based on the corresponding geometries obtained from μ CT.

Combining stiffness and strength provides a perspective in which density no longer appears explicitly. For a given grain type group, one mechanical property could in principle be used to estimate the other. More generally, the distinct scaling regimes suggest that a single idealized cellular architecture is insufficient to represent all snow types. Simplified mechanical models should preserve not only the amount of ice but also the dominant mode of deformation associated with the microstructure.

3.4. *Application in SNOWPACK*

To illustrate the practical use of these results, we applied them to a SNOWPACK simulation for

Weissfluhjoch, Davos, during the 2024/25 winter season (Figure 2). Layers belonging to the investigated grain type groups were assigned to either the stretching- or bending-dominated regime. Grain types outside the investigated groups were not assigned to either regime. The grain type-dependent density relations were then used to estimate the effective elastic modulus and the compressive strength of individual snow layers. The resulting time series shows how these mechanical properties evolve within the simulated snowpack as a function of density and grain metamorphism.

These parameterizations could provide time-resolved, layer-specific mechanical properties as inputs to physical avalanche release models. Stiffness and strength alone do not determine the likelihood of avalanche release, but must be combined with descriptions of the stress state, slab properties, and fracture behavior (e.g. Rosendahl and Weißgraeber 2020). Coupling such mechanical parameterizations with detailed snow cover simulations therefore represents one step towards mechanics-based, time-resolved estimates of snowpack stability.

4. CONCLUSIONS AND OUTLOOK

Density was the dominant first-order predictor of stiffness and compressive strength, yet microstructure influenced how these properties depended on density. Grain type-specific power laws captured these systematic differences and provide directly usable estimates when grain type and density are known. The SNOWPACK example shows how these parameterizations can be applied using variables already available in a detailed snow cover model.

The combined scaling of stiffness and strength further separated the investigated weak layer types into distinct mechanical regimes. FC/DH and SH showed predominantly stretching-like behavior, whereas DF/RG were closer to bending-dominated structures. This classification describes the effective response of the microstructure and does not imply that deformation occurs exclusively through either stretching or bending.

The results presented here are limited to uniaxial compression over a relatively narrow range of temperatures and strain rates. For applications in avalanche release modeling, the mechanical response must be investigated under multiaxial loading together with the corresponding microstructure. Recent combined compression–shear experiments on buried surface hoar provide an ex-

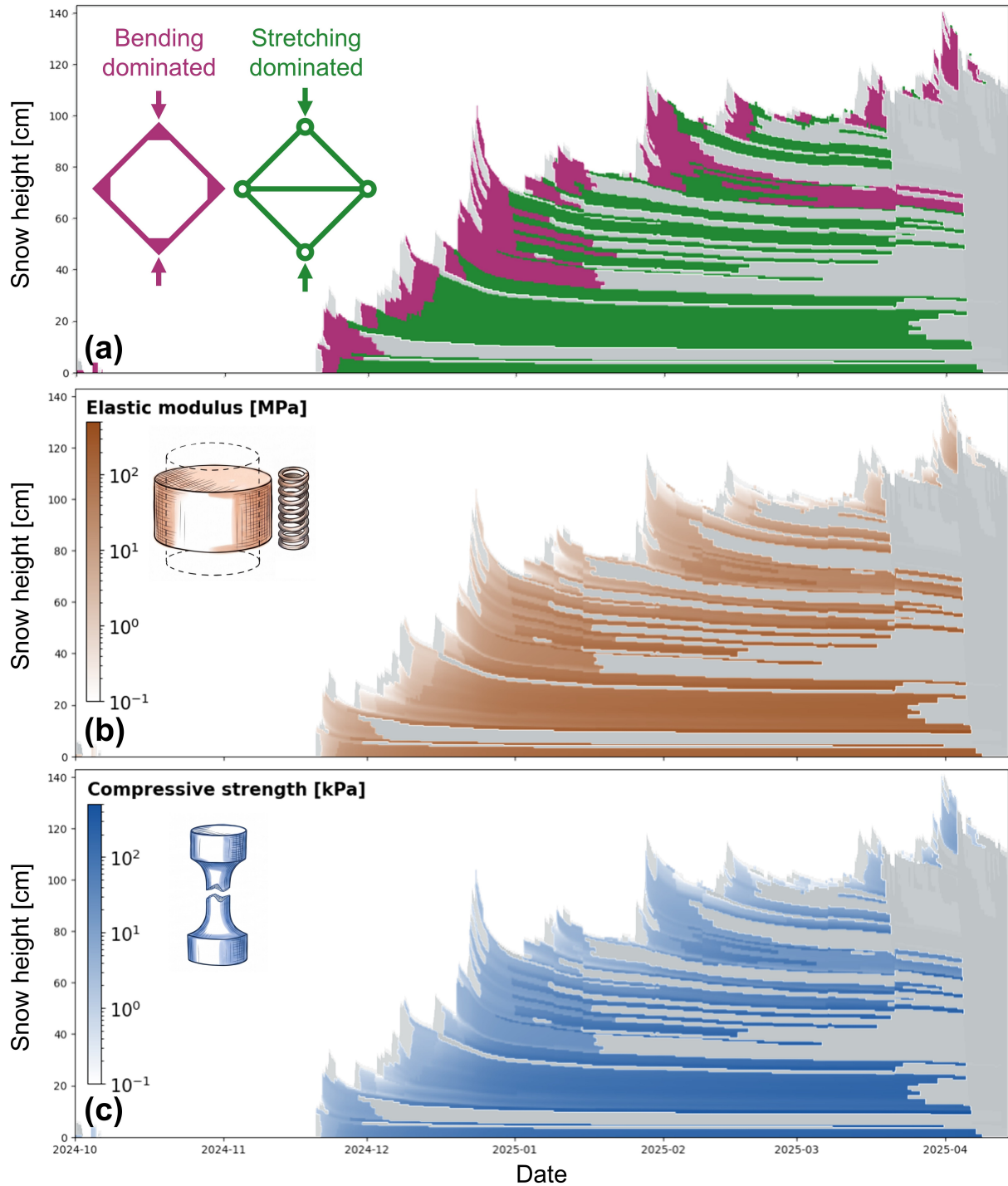


Figure 2: Application of the proposed mechanical simplifications to a SNOWPACK simulation for Weissfluhjoch, Davos, during the 2024/25 winter season based on the primary grain type. (a) Snow layers assigned to predominantly stretching- or bending-dominated behavior based on their simulated grain type. Layers outside the investigated grain type groups are shown in grey. (b) Effective elastic modulus and (c) compressive strength estimated using the corresponding grain type-dependent density parameterizations.

ample of this approach and yielded closed, approximately elliptical failure envelopes (Schöttner et al. 2026a). Comparable measurements, ideally with specimen-resolved μ CT, are now required for other weak layer types to determine how mi-

crostructure controls multiaxial stiffness and failure and to find more general constitutive descriptions.

DATA AVAILABILITY

The experimental and microstructural dataset is available on EnviDat (Schöttner et al. 2025b), DOI: 10.16904/envidat.648.

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