

MICROMECHANICAL APPLICATIONS TO RADIATION RECRYSTALLIZED SNOW

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ABSTRACT: Buried radiation recrystallized layers are a challenging hazard to contend with in avalanche terrain. After forming, these layers are weak and elusive in a snow profile due to their thin structure. It is difficult to accurately study these layers' mechanical properties by approximating them as a continuous medium. Adjusting the scope of the observed problem down to the micro-scale leads to some new ways to describe the mechanical behavior of snow. The evolution of the microstructure of radiation recrystallized snow was recorded with the use of micro-CT scans obtained at specific time intervals. These 3-D reconstructions allow for further analysis of the effective mechanical properties of snow. The 3-D microstructure from the micro-CT scans is used as the geometry in computer simulated mechanical tests (finite element method). This approach is advantageous since the mechanical properties of ice are known with greater precision than those of snow. Using the microstructural geometry and incorporating ice network damage, effective material properties such as stiffness and strength compare positively to macro-scale mechanical testing on non-radiation recrystallized snow. However, there is greater uncertainty in the underlying material properties of the ice network for the radiation recrystallized case. There is still more work to be done in understanding the mechanical properties of weak layers in snow is essential to better quantify the hazards these layers present.

KEYWORDS: microstructure, radiation recrystallization, modeling, simulation, stiffness, strength

1. INTRODUCTION

Radiation recrystallized snow layers are a frequently encountered avalanche hazard in sunny mountainous regions. The danger lies in the microstructural changes that take place during the formation of this type of layer. The conditions required for formation of radiation recrystallized layers are well documented as are recent approaches toward analyzing the macro-scale mechanical performance of snow based on studying the micro-scale arrangement of ice grains. Here, a preliminary account is given of the application of finite element methods utilizing the real microstructural geometry recorded from X-ray computed tomography (micro-CT) scans of non-layered and radiation recrystallized layered snow developed in the laboratory. Macro-scale mechanical tests were performed in shear for comparison with the modeled results. One test case is presented here with the anticipation of applying similar techniques in the future to a larger data set.

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2. BACKGROUND

2.1 Radiation Recrystallization Formation

Near surface temperature gradients are responsible for the formation of faceted crystals within the existing snowpack (Colbeck 1989). These faceted crystals are termed radiation recrystallized facets since these temperature gradients develop as a result of subsurface warming from incoming shortwave radiation and surface cooling from outgoing longwave radiation (Colbeck 1989; Birkeland 1998). Several studies have progressively advanced our understanding of the formation of radiation recrystallized layers (Morstad et al. 2004; 2007; Slaughter et al. 2008; 2009; 2011). Furthermore, procedures for simulating environmental conditions conducive for radiation recrystallization were initially developed by Morstad et al. (2004; 2007) and refined by Slaughter et al. (2008; 2009; 2011). Specific conditions utilized for this study are detailed by Walters and Adams (2012; 2014) and are briefly summarized below in the methods section.

2.2 Micromechanics

The focus of this study is to better understand and explain the macro-scale mechanical effects of the formation of radiation recrystallized snow as a re-

sult of the microstructural changes that take place. The primary method employed here utilizes a computer simulation method called Finite Element Analysis (FEA). This method involves splitting the desired geometry into smaller, finite sections of material and applying virtual loads and/or displacements to the discretized geometry to numerically solve for internal loads and deformation.

Numerous studies have modeled snow as one continuous medium; however, this method does little to explain the effects of the microstructural arrangement of ice grains on the overall macro-scale mechanical response of the snow.

In other approaches, the underlying ice structure is used as the geometry for FEA study. Using material properties for ice (which are more precisely known than for snow), one can determine the effective material properties for snow based on the mechanical response of the microstructure provided. Recent attempts have been made to utilize the snow's microstructure directly (Schneebeli 2004; Srivastava et al. 2010; Theile et al. 2011; Chandel et al. 2014). These recent studies provide ample background for the basis of this current model. The study by Theile et al. (2011) is not as relevant to this study since it utilized a simplified beam element model for studying slow strain rate creep behavior. Both Schneebeli (2004) and Srivastava et al. (2010) showed the correlation of material stiffness parameters of snow to the direction of an induced temperature gradient. However discrepancies existed between measured stiffness values and calculated stiffness. The effects of the sample volume used in analysis was investigated by Chandel et al. (2014) and proved useful for this study.

3. METHODS

The sample presented here is a single test set from a larger study aimed at understanding and explaining the development of a directionally oriented weak layer of radiation recrystallized facets using multiple microstructural methods.

3.1 *Snow Sample Preparation*

This particular sample was prepared and tested at the Subzero Science and Engineering Research Facility at Montana State University beginning December 13, 2013. Fragmented dendritic crystals were collected in the laboratory using a snow breeder which transports moist air past nucleation sites. These collected crystals are sieved through a 0.7mm grid to a depth of 10cm over the top of well rounded, sintered snow. After standing and

sintering for several hours, the sieved snow resembled crystals of uniform grain size of 0.1 mm to 0.25 mm. This resulted in a density of approximately 147 kg m^{-3} .

The sample was tested in shear twice: once before radiation recrystallization, and once after formation and burial of a radiation recrystallized layer. The mechanical test will be described in the next subsection. Testing twice allows for comparison of the relative change in material properties before and after recrystallization has taken place.

Prior to each mechanical test, a small volume of snow (3 cm diameter x 5 cm high) is extracted to obtain a micro-CT scan of the microstructure using a SkyScan 1173 X-ray Computed Tomography scanner. This device creates a set of images that can be reconstructed to analyze and visualize the three-dimensional microstructure of snow.

In between mechanical tests, the snow sample is subjected to conditions which induce radiation recrystallized facet formation. Selected parameters in Tbl. 1 are detailed in Walters et al. (2010), and Walters and Adams (2012; 2014).

Tbl. 1: Environmental parameters for laboratory induced radiation recrystallization.

<i>Parameter</i>	<i>Value</i>	<i>Units</i>
Ambient Air Temperature	-15	°C
Incoming Shortwave Radiation	750	W m^{-2}
Incoming Longwave Radiation	225	W m^{-2}
Sky Temperature (Cold Ceiling)	-50	°C
Duration	12	hrs

3.2 *Mechanical Test*

The mechanical tests performed before and after recrystallization were identical except for the absence or presence of a radiation recrystallized layer. The shear tests are conducted using a 250 cm^2 shear frame sintered in place following the protocol established in Walters and Adams (2012; 2014). The physical setup is shown in Fig. 1. A surface parallel shear load was supplied with a GeoTac-GeoJac actuator using displacement rate control at 0.2 mm s^{-1} . The shear load was measured in line with the actuator at a rate of 1,000 Hz. Displacement and deformation was logged using an optical strain measuring device (GOM-Aramis) recording at 15 frames per second. This system allows for high resolution mapping of strain and displacement anywhere on the face of the sample. Samples were loaded to failure.

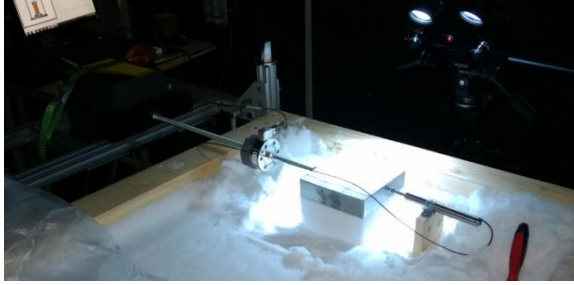


Fig. 1: Shear test setup with 250 cm² frame, load actuator, and optical strain measuring device.

3.3 Model Parameters

A sub-volume of snow is selected from the micro-CT scanned sample containing a buried radiation recrystallized layer. A sub volume of 4mm x 4mm x 6mm tall was selected which adequately captures the thickness of the radiation recrystallized layer while reducing the number of required elements. A sample of this size should be sufficient for avoiding edge effects created by samples of even smaller volumes (Chandel et al. 2014). The same dimensions were used to extract a sub-volume from the non-radiation recrystallized sample.

The reconstructed samples are processed in Materialise® Mimics software to convert the reconstructed voxel data to a 4-node tetrahedral mesh for use in ANSYS. After processing, each microstructural volume contained approximately 225k elements (see Fig. 2).

Initial testing utilized isotropic polycrystalline ice properties from Petrenko and Whitworth (1999). This resulted in overly stiff behavior. Properties in Petrenko and Whitworth (1999) are derived from ice grown from freshwater baths. A later study by Kermani et al. (2007; 2008) on the properties of atmospheric ice provided more appropriate stiffness and strength parameters for ice and were further refined to the properties listed in Tbl. 2.

As will be discussed following the results, it was prudent to input anisotropic single crystal properties for use with the radiation recrystallized sub-volume. The subscripts 1, 2, and 3 refer to the coordinate axis direction in relation to a single ice crystal with subscript 3 being parallel to the c-axis. Subscripts 4, 5, and 6 refer to the shear behavior. The directional stiffnesses listed in Tbl. 3 (generalized Hookes Law; right handed coordinate system; 3 direction is perpendicular to the snow surface) are used instead for the radiation recrystallized sample. The failure criteria however remained

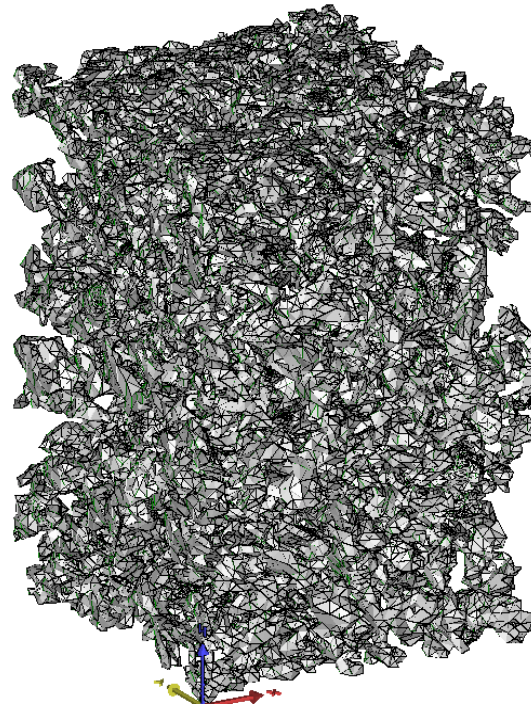


Fig. 2: Volumetric mesh of 4-node tetrahedral elements developed directly from micro-CT scans. Dimensions are 4mm x 4mm x 6mm.

unchanged from what was listed in Tbl. 2. These values are based on properties listed in Petrenko and Whitworth (1999) but adjusted to reflect the reduced stiffness of atmospheric ice utilized in the non-radiation recrystallized setup.

Tbl. 2: Ice material properties utilized for the non-radiation recrystallized microstructural finite element analysis.

Parameter	Value	Units
Isotropic Young's Modulus	2.00	GPa
Poisson's Ratio	0.325	-
Maximum Tensile Stress	3.00	MPa
Maximum Compressive Stress	5.50	MPa

Both samples were constrained with a fixed boundary condition on the bottom nodes, and a displacement boundary condition on the top nodes. The displacement was applied in incremental load steps equal to the same rate as mechanical testing performed in the lab. In between each load step, elements were analyzed for their stress state and any elements exceeding to allowable stresses as listed in Tbl. 2 were removed from the analysis. Load steps continued until the solution could no longer converge.

Tbl. 3: Directional stiffness parameters utilized in the radiation recrystallized microstructural finite element analysis. The 3 direction is parallel to the crystals' c-axis and also perpendicular to the snow surface.

Parameter	Value	Units
$C_1 = C_2$	1.367	GPa
C_3	1.476	GPa
$C_{12} = C_{21}$	0.683	GPa
$C_{23} = C_{32} = C_{13} = C_{31}$	0.551	GPa
$C_{44} = C_{55}$	0.301	GPa
$C_{66} = (C_{11} - C_{22})/2$	0.342	GPa

4. RESULTS

4.1 Laboratory Mechanical Test

In the preliminary shear test on the non-radiation recrystallized sample, stress and strain developed nearly linearly until the point of failure. Shear strain was distributed uniformly across the depth of the sample as seen in Fig. 3.

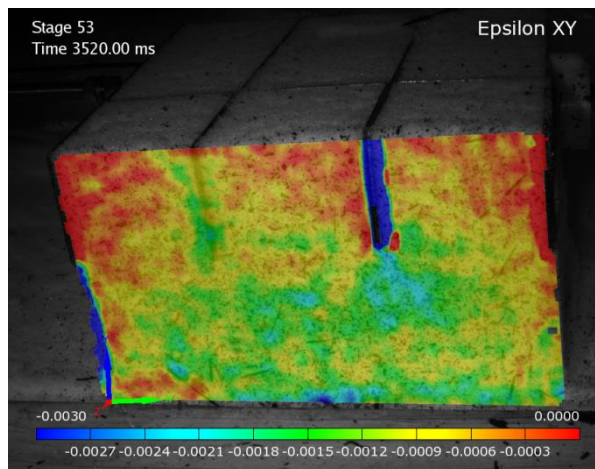


Fig. 3: Shear strain (rad) in the non-layered sample just prior to failure. The shear load is applied right to left across the frame pictured at the top of the sample.

Due to the bending forces imparted on the column with no clear weak interface, this sample failed by the nucleation of a tensile crack parallel to the surface located at the lower right corner in Fig. 3.

Similarly, the shear test on the sample containing a radiation recrystallized layer started off with a nearly linear stress/strain profile. However, the strain was concentrated in the location of the radiation recrystallized layer as seen in Fig. 4. Unlike the non-layered sample, the failure seemed more

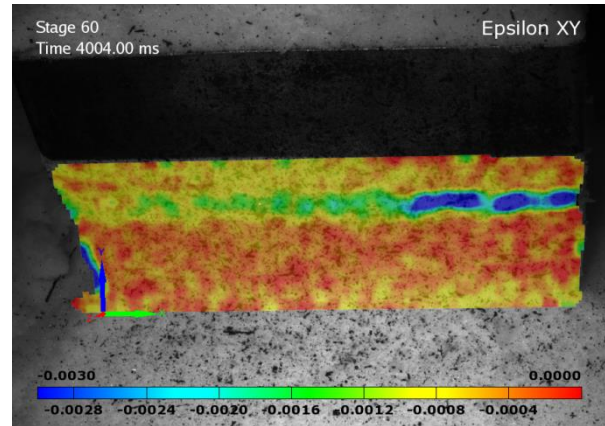


Fig. 4: Shear strain (rad) in the layered sample just prior to failure. The shear load is applied right to left across the frame pictured at the top of the sample.

induced by shear behavior rather than bending forces.

A comparison of the calculated stress and strain curves of both tests are displayed in Fig. 5. The calculated shear moduli and strengths are tabulated in Tbl. 4. Both the shear moduli and shear strengths decreased from no weak layer present to the presence of a radiation recrystallized weak layer.

Tbl. 4: Material properties calculated from laboratory shear testing on non-layered and radiation recrystallized layered samples.

Parameter	Value	Units
Non-Layered Shear Modulus	1.71	MPa
RR Layered Shear Modulus	0.443	MPa
Non-Layered Ultimate Shear Strength	2.15	kPa
RR Layered Ultimate Shear Strength	0.668	kPa

4.2 Finite Element Analysis

The finite element analysis showed promise toward predicting the effective elastic moduli of snow when compared to real mechanical tests. Although the material properties of ice are altered between the non-layered and radiation recrystallized sample, this adjustment allows the model to behave similarly to the results observed from the laboratory tests. The model was run in shear similar to the mechanical test performed in the lab. In addition, vertical compression was also simulated.

The shear behavior of the finite element simulation is shown in Fig. 6 below. Again, the stress/strain relationship of both the non-layered and radiation recrystallized layered samples start off linear

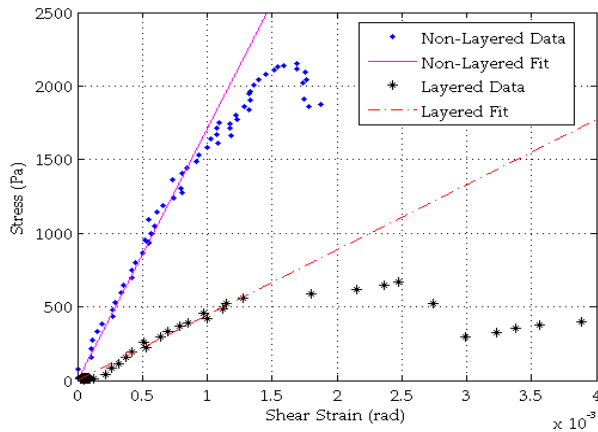


Fig. 5: Stress and strain curves for the laboratory shear tests. Best fit lines are provided in the linear sections for calculating the shear moduli of each test respectively.

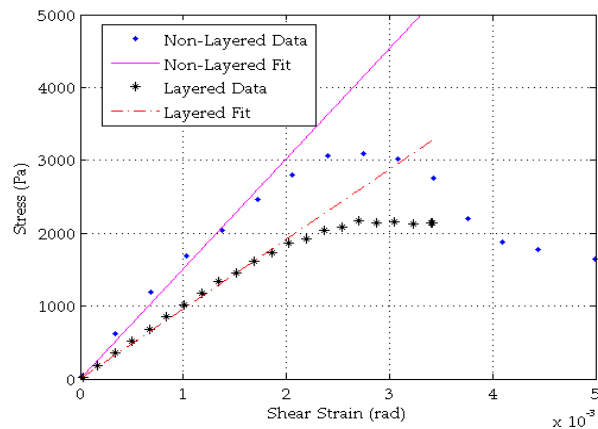


Fig. 6: Shear stress and strain curves from the finite element model run on both non-layered and radiation recrystallized layered snow samples.

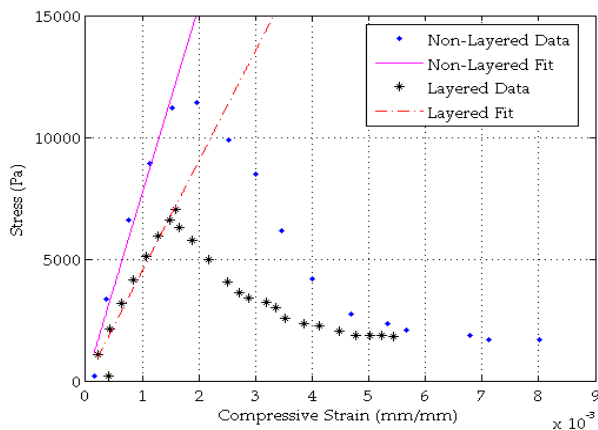


Fig. 7: Compressive stress and strain curves from the finite element model run on both non-layered and radiation recrystallized layered snow samples.

before yielding and failure is reached. With the radiation recrystallized layered sample, the element formulation became unstable before a final load step could be completed showing total failure of the sample. The material properties derived from this FEA model run are summarized in Tbl. 5

In addition to becoming less stiff and strong in shear, the simulated results in compression showed similar trends. The compressive stress and strain curves for the finite element analysis are shown in Fig. 7 below. The material properties calculated from the compression run are summarized in Tbl. 5.

Tbl. 5: Material properties calculated from finite element simulations on non-layered and radiation recrystallized layered samples.

Parameter	Value	Units
Non-Layered Shear Modulus (FEA, parallel to surface)	1.51	MPa
RR Layered Shear Modulus (FEA, parallel to surface)	0.958	MPa
Non-Layered Young's Modulus (FEA)	7.71	MPa
RR Layered Young's Modulus (FEA)	4.52	MPa
Non-Layered Ultimate Shear Strength (FEA, perpendicular to surface)	3.09	kPa
RR Layered Ultimate Shear Strength (FEA, perpendicular to surface)	2.17	kPa
Non-Layered Ultimate Compressive Strength (FEA)	11.4	kPa
RR Layered Ultimate Compressive Strength (FEA)	7.03	kPa

5. DISCUSSION

Density and microstructure both significantly influence the mechanical properties of snow. The ice volume fraction of the non-layered sample compared to the radiation recrystallized sample analyzed here differed negligibly at 20.1% and 21.5% respectively. From the experimental shear test results alone, it is evident that the microstructural changes impacted the relative change in material properties.

Utilizing the non-layered sample, the effective stiffness of the experimental result and simulated result with the use of isotropic polycrystalline atmospheric ice correlates well. The simulation of stresses on uniform, rounded snow is interesting by itself since it demonstrates that the stress distribution throughout the supporting ice network is not uniform. The results in Fig. 8 show a mostly unstressed microstructure with large stress conce-

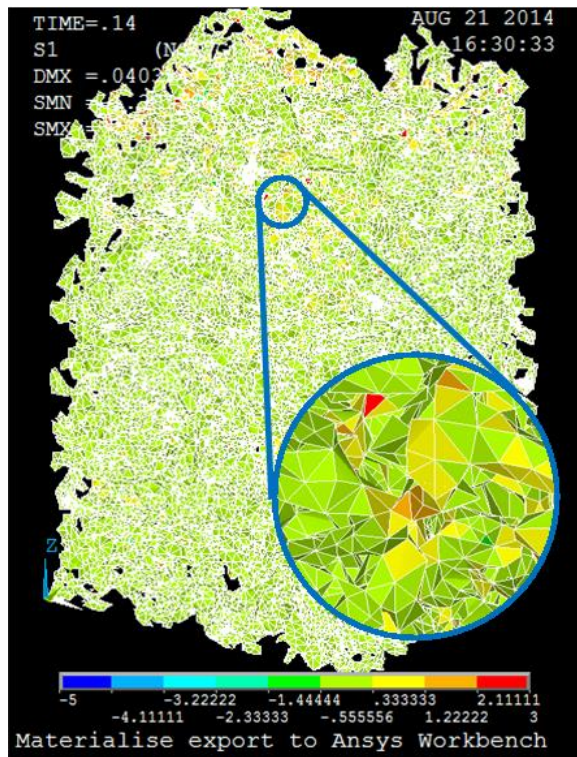


Fig. 8: Maximum principal stress (MPa) result from the simulated shear test on the non-layered sample. Most of the sample remains unstressed whereas stress concentrations form at constrictions in the ice network (inset).

concentrations located at constrictions in the ice network thought to be locations of bonds between grains.

Following radiation recrystallization, a thin layer of faceted crystals within the radiation recrystallized zone seem to exhibit a columnar type microstructure similar to the chains of facets observed in depth hoar (Staron et al. 2014) -albeit on a much smaller scale. This column like formation alone was thought to be the factor that makes radiation recrystallized layers more susceptible to failure. More details on the crystal growth during metamorphism are supplied in a parallel study with Adams and Walters (2014).

Unexpectedly, when utilizing isotropic ice properties for simulating shear loads on the radiation recrystallized sample, the sample behaved stiffer than its non-layered pair, contrary to the experimental result tested in the lab. Perhaps the microstructural rearrangement associated with radiation recrystallization creates a patterned arrangement of single ice crystal axes. The resulting geometry and alignment of crystal axes together may contribute to the weakness associ-

ated with these layers. However, identifying a preferred crystallographic orientation is difficult since both a-axis and c-axis growth is observed (Fig. 9).

Although the specific arrangement of crystal axes is too difficult to determine, material properties in the finite element model were changed to the transversely isotropic properties associated with single ice crystals with their c-axes aligned vertically (perpendicular to the snow surface). This was done to investigate how simulated results would respond to such an ordered arrangement. This modification resulted in simulations of shear tests that more closely resembled the behavior observed in the laboratory shear test (compare Fig. 5 and Fig. 6).

Interestingly, the simulated compression results seem to show support for the columnar type structure of the radiation recrystallized crystals observed. Near the end of the simulated compression test on the non-layered sample, failed elements are distributed evenly throughout the sample (Fig. 10a). In contrast, the same compression simulation on the radiation recrystallized layered sample resulted in concentrations of failed elements both above and below the region associated with the zone of columnar recrystallized facets (Fig. 10b). A columnar sub-structure should be more stable when aligned with the compressive load than the neighboring regions of random microstructural arrangements.

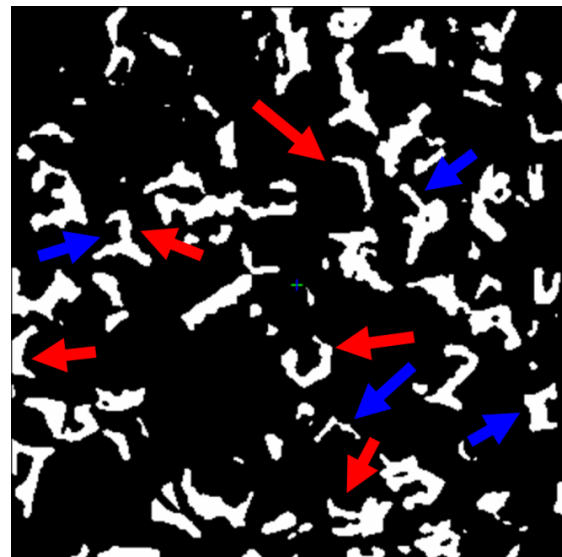


Fig. 9: Micro-CT cross section parallel to the snow surface showing several hexagonal c-axis growth crystals (red arrows) and square a-axis growth crystals (blue arrows) oriented with their growth axes nearly perpendicular to the snow surface.

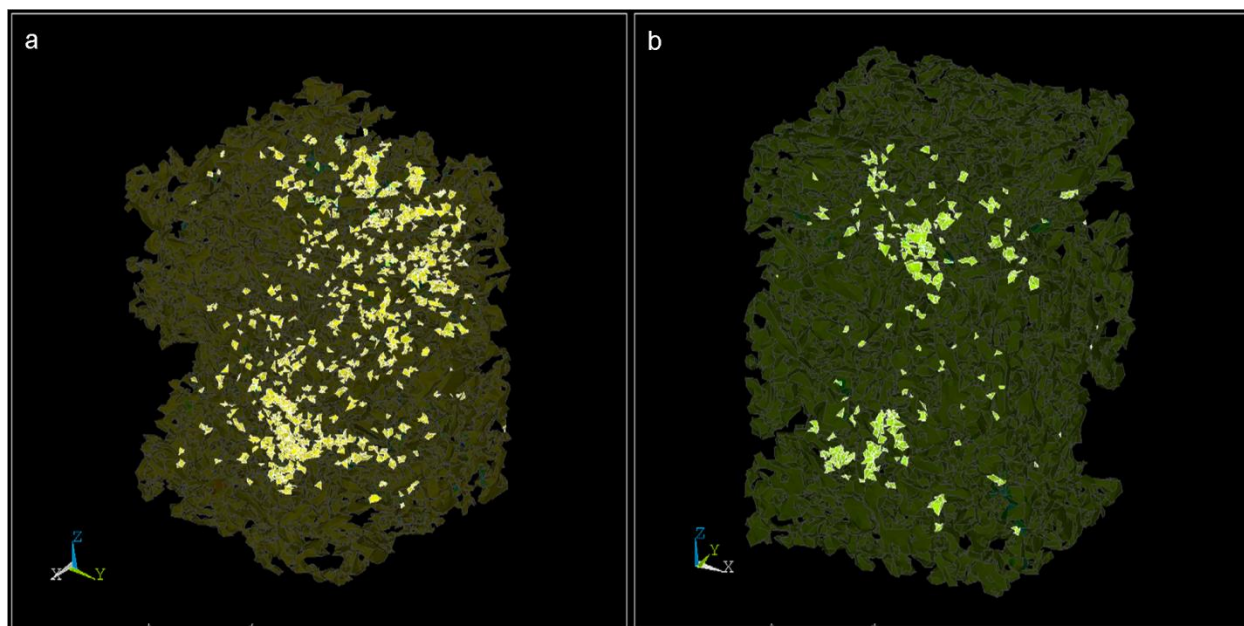


Fig. 10: A comparison of the locations of failed elements during simulated compression on:(a) the non-layered sample and (b) the radiation recrystallized sample. Brightened elements represent elements that have failed.

6. CONCLUSIONS

Investigating the weaknesses associated with radiation recrystallized snow layers deserves a close look at the microstructure of the snow. Using an initial test case, mechanical shear testing of this particular sample resulted in a significant reduction of both shear stiffness and shear strength. To try to understand the role of the microstructure on the mechanical performance of such a layer, finite element simulations were performed on the actual geometry of the ice network derived from micro-CT scans. While initial simulations on uniform, non-layered snow were positive, simulation of the more patterned arrangement of radiation recrystallized layers proved more difficult. There are still several uncertainties that exist regarding the appropriate material properties for use with radiation recrystallized samples. Analysis of the larger data set in which this particular test case originated from is currently underway.

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