Cold Regions Science and Technology 116 (2015) 56–64

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Determination of failure envelope for faceted snow through numerical simulations

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ARTICLE INFO

Article history:
Received 18 December 2014
Received in revised form 13 April 2015
Accepted 17 April 2015
Available online 22 April 2015

Keywords:
Failure envelope
X-ray micro-CT
Representative volume element
Damage

ABSTRACT

Failure of weak layer in a snowpack, lying on a slope, due to combined compression and shear loading is a major factor in release of slab avalanche. Failure envelopes for FCso and FCsf snow (Fierz et al., 2009) were determined using finite element (FE) modeling. Snow samples of FCso and FCsf from the field were taken to the laboratory and X-ray tomography was performed on these to reconstruct 3D microstructure of each snow type. From the images representative volume elements (RVEs) of each type was constructed. The RVEs were subjected to combined loading to predict the failure envelopes. These failure envelopes were compared to the data published earlier and showed similar trends.

1. Introduction

Slab avalanches usually occur due to failure of a weak layer or an interface underlying a strong slab (McClung and Schaerer, 1993). The weak layer can be a depth hoar layer, a near surface faceted particle layer, a buried surface hoar layer or a buried graupel layer in a snowpack. The layers in a snowpack lying on a slope are subjected to simultaneous compressive and shear stresses due to self-weight and additional loads resulting from skier's weight, explosives, earthquakes or due to new snow. If the resultant of these stresses exceeds a limiting value failure can initiate in the pack. To get a qualitative idea about the weakness present in the snowpack, different stability tests such as Rutschblock test (Föhn, 1987), stuffblock test (Birkeland et al., 1996), compression test (Jamieson and Johnson, 1997) and shovel shear test (Tremper, 1994) have been practiced by skiers and avalanche researchers. The initiation of slab avalanche release is caused by the combined compressive and shear loading and due to this reason researchers started to explore the effect of combined loading on snow and avalanches. Perla and Beck (1983) and Zeidler and Jamieson (2006) conducted combined compressive and shear loading experiments and observed an increase in the shear strength with normal compressive load for different snow types. Nakamura et al. (2010) investigated the behavior of rounded polycrystals snow and measured the shear strength for a varying compressive load and reported a linear increase in shear strength with compressive pressure. Reiweger et al. (2010) developed a load controlled apparatus to study the failure of snow under combined loading conditions. Reiweger and Schweizer (2010) studied the failure of sandwiched surface hoar samples as well as faceted and depth hoar snow samples (Reiweger and Schweizer, 2013) using the same instrument developed by Reiweger et al. (2010). In another recent experimental study, Chandel et al. (2014b) reported failure envelopes for round grain snow (RGsr), faceted snow (FCso) and near surface faceted particles snow (FCsf) using combined compression and shear loading experiments. Podolskiy et al. (2014) developed a portable shear apparatus to assess the strength of snow interfaces under different normal and shear pressures.

The focus of the above studies was to estimate the snowpack stability or strength and relating the strength trends to the microstructure or micro-mechanics was not attempted. Lately, direct 3D reconstruction of snow microstructure (Brzoska et al., 1999; Schneebeli and Sokratov, 2004) at resolutions down to a few microns has become possible with X-ray micro-computed tomography (μ-CT). Schneebeli (2004), Srivastava et al. (2010), Yuan et al. (2010) and Theile et al. (2011) applied different numerical techniques on the 3D microstructure of snow to obtain its mechanical properties/behavior. The constitutive behavior of ice determines the mechanical behavior of snow, which in turn helps to understand the slab avalanche release mechanism and hence snowpack stability. Schleef and Löwe (2013) conducted creep experiment on new snow and studied the densification and change in specific surface area (SSA) with deformation. Wang and Baker (2013) conducted compression experiments on different snow types and by using X-ray tomography described the evolution of microstructure. Köchle and Schneebeli (2014) utilized X-ray tomography and FE analysis to demonstrate the contrast in microstructural and elastic properties to identify weak layer present in the snowpack. Chandel et al. (2014a)

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http://dx.doi.org/10.1016/j.coldregions.2015.04.009
0165-232X/

reconstructed the microstructure of RGsr snow using X-ray tomography and numerically simulated the mechanical response of RGsr snow by assigning damage based elasto-plastic constitutive law to the ice matrix of snow. Hagenmuller et al. (2014a) reported that the mechanical response of snow is directly dependent on minimum cut density (MCD) and determined its tensile strength through numerical simulations. Recently failure envelopes for weak snow layers were developed using discrete and finite element modeling (DEM and FEM respectively) from idealized 2D model (Gaume et al., 2014; Podolskiy et al., 2015) under the combined effect of compressive and shear loading. Reiweger et al. (2015) represented the failure criterion for weak snow layers in the normal stress–shear stress by Mohr–Coulomb with Cap (MCC) envelope. For small compressive stresses (corresponding to high slope) the failure envelope was modeled by conventional Mohr–Coulomb criterion. For high compressive stresses (corresponding to small slope) cap region was modeled separately and included in the failure envelope. In the present study, numerical simulations and actual 3D microstructure of FCso and FCsf snow samples are used for determination of failure envelopes under the combined effect of compressive and shear loading. The methodology described by Chandel et al. (2014a) was used to extract the deformation behavior of FCso and FCsf snow samples, and determine their strength under different loading conditions.

2. Micro-CT imaging and Image reconstruction

In the experimental study, Chandel et al. (2014b) determined the failure envelopes for two weak layers, FCso and FCsf snow layers. In the present study we decided to carry out the numerical simulations on these two types of weak layers and reproduce failure envelopes. Snow and Avalanche Study Establishment (SASE) has a research station at Patseo in Great Himalayan range at an altitude of 3800 m amsl where a weekly pit study is carried out on horizontal ground to keep an eye on the evolution of snowpack. During pit observations FCso and FCsf snow layers were identified. These layers are very weak as well as very fragile at low-density and could not be extracted from the snowpack easily. Due to this problem of handling the weak layer snow samples, only higher density snow samples were extracted and transported in insulated boxes to environmental chamber SASE (Manali, India) via helicopters, for X-ray scanning. Due to dominance of grain growth direction along gravity, microstructural fabric also shows anisotropic behavior therefore a special precaution was taken during extraction of these samples such that during X-ray scanning, the vertical axis of sample and direction of grain growth coincide. The snow samples of FCso and FCsf were weighed and found to have densities of 412 kg m^{-3} and 251 kg m^{-3} respectively. These were next imaged at a temperature of −10 °C using Skyscan 1172 high resolution μ-CT system. During the scanning the specimen rotates with a fixed rotation step up to 180° and at each angular position, shadow or projection images are captured at the detector. The details of the scanning parameters are given in Table 1.

From the projection images, cubic volumes were reconstructed using modified Feldkamp cone beam software (NRecon, SKYSCAN). The reconstructed 3D images of snow were gray scale images and have an isotropic resolution of 7.96 μm, resulting in 1185 images of 1185 × 1185 pixels for FCsf snow and isotropic resolution of 10.79 μm, resulting in 774 images of 774 × 774 pixels for FCso snow, which is a very large volumetric data for processing. To ease the problem of processing and increase the size of sample that can be handled, the data was coarsened such that one voxel corresponds to 23.88 μm and 32.37 μm for FCsf and FCso snow respectively. These faceted snow types can have very small structural details (e.g., bonds) which may be poorly represented at coarse resolutions. Therefore to ensure that there is not much variation between the scanned microstructure and coarse resolution microstructure, structural thickness distributions (STD) for both FCso and FCsf snow were determined and plotted (Fig. 1). It was observed from the distributions that for lower structural thickness (which represents small details of microstructure) percentage at fine resolution was higher but difference was not significant. Hence microstructures with coarse resolution were used for numerical simulations.

3. Numerical simulations

Snow is a porous material with a solid skeleton or matrix of ice. The mechanical properties/response of snow strongly depends on the morphology of the ice phase distribution in space. Ice volume fraction (φ_i), specific surface area (SSA), connectivity density (β_{1V}) etc. are the microstructural parameters which are used to estimate the morphology of porous materials (Arns et al., 2002). These microstructural parameters for FCsf and FCso snow samples scanned in the present study are given in Table 2. The values of these microstructural parameters indicate that the matrix of ice for FCsf snow compared to FCso snow is very weak and hence more damage is expected for even very small loading.

Analyzing stresses in a snowpack using complete microstructure is numerically prohibitive. Analysis methods, therefore, approximate porous structures by an equivalent homogeneous material (EHM) and the properties of which are derived using a representative volume element (RVE).

3.1. Representative volume element

Maugin (1992) suggested that a quantitative relation can be determined by using homogenization methods, where the heterogeneous material is replaced by an EHM. The equivalent continuum is defined in such a way that, in a certain sense, it has the same average mechanical response as the actual heterogeneous material (Nemat-Nasser and Hori, 1993). This equivalent continuum is called a representative volume element (RVE) and for snow Chandel et al. (2014a) have used a cubical RVE. In snow studies, Srivastava et al. (2010) and Chandel et al. (2014a) used consistency analysis to determine the size of RVE with respect to ice volume fraction ($V_{\varphi_i}^{RVE}$). Kanit et al. (2006) suggested that for heterogeneous porous material any sub-volume size can be used as the RVE such that a sufficient number of realizations are considered to obtain desired precision. Chandel et al. (2014a) used statistical RVE analysis and found that if the size of RVE (i.e., $V) = 8\,V_{\varphi_i}^{RVE}$, the standard deviation for ultimate strength reduced by 50% but the error involved remained ≈ 13% for RVE sizes of 1.791^3 mm^3 and 3.582^3 mm^3 with 64 and 8 number of realizations respectively. Köchle and Schneebeli (2014) determined the size of the RVE by calculating Young's modulus, for three different snow types, with an assumption that the snow in given volume was isotropic. The RVE calculations were carried out from four different corners and the cube side length was increased

Table 1
CT parameters for scanning snow.

Snow sample	X-ray tube		Radiograph acquisition		Volume reconstruction	
	Voltage (kV)	Current (μA)	Angular displacement step (°)	Exposure time (ms)	Pixel size (μm)	Reconstruction volume (voxels)
FCso	80	100	0.3	1178	10.79	774^3
FCsf	80	100	0.3	1178	7.96	1185^3