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Abstract *The paper presents a prototype of a new device for measuring the shear strength of snow specimens in-situ. The resistance to sliding of a snow slab on a mountain slope is a key parameter in snow mechanics. The proposed apparatus acts as a sampler, to obtain a nearly undisturbed specimen, and as a shear box, similar to those used in the laboratory, with complete control of the test procedure. The main components of the device are a pneumatic system, for the application of normal and shear forces to the specimen, a real-time controller for commanding and recording of the data, and a computer. The apparatus can be carried to the place of the experiments and operated by a team of two researchers. Calibration and preliminary tests are also described in the paper.*

1   Introduction

The assessment of the stability conditions of the seasonal snowpack on mountain slopes is an important component of the actions of prevention and mitigation of natural hazards in the alpine environment. Avalanche risk is of concern not only to backcountry skiers, but also to officials in charge of the safety of ski resorts, or to planners of new infrastructures potentially prone to such catastrophic events.

Predicting the mechanical behaviour of snow is a difficult task. In spite of being a material constituted only by almost pure water, snow shows large variations of strength and deformability both in space, like all natural geomaterials, and in time, on a scale comparable to the duration of an experiment. Temperature-driven metamorphism of the snowpack leads to dramatic changes of the structure of snow at microscopic scale, with corresponding variations of the strength of the bonds between the grains (see, e.g., [9, 13]). Therefore, in order to obtain experimental data reflecting the real conditions of the snowpack, it is crucial to test a nearly intact or practically undisturbed specimen. These conditions may be fulfilled in two ways: an accurate sample recover, handling, and conservation until the laboratory test is performed, or through in-situ testing on a portion of the snowpack in its natural condition. Moreover, it is well known that the variation of the stress field in the specimen, due to the sampling operations, e.g., the removal of the overburden pressure, may be important and worth of being reproduced before testing.

In the field of avalanche risk assessment, a simple yet effective tool used by experts to evaluate the stability of snow slopes is a quick shear test performed on the chosen snow layer, by means of a light, hand-driven shear frame. The output of the test is a strength index of the snowpack, related to the force needed to shear the sample, in its nearly undisturbed conditions. For an introductory treatment to the topic of safety against avalanches see, e.g., McClung and Schaerer [6].

The present research is devoted to a different, though related, objective: namely, the measurement of the shear strength of a natural deposit of snow in accurately reproducible testing conditions. To this purpose, a new apparatus has been designed, which maintains the concept of undisturbed in-situ sampling, but permits to control precisely all the test parameters and to acquire reliable data. Of course, the prototype apparatus described in the paper is much more complex than the hand-driven shear frame, and it can be used only by trained operators.

2   Snow properties

2.1   General

In situ observations show that snow slab avalanches occur where a harder thick layer overlies a thinner weak layer [5]. The mechanisms of instability depend on both strength and stress-strain characteristics of the snow. These are very difficult to define as they depend on many variables in space and time, such as snow density, structure and size of snow crystals and grains, net surface area of inter-grain contacts per unit volume, orientation of snow crystals, temperature, applied pressures [16]. As a result, the mechanical properties of snow undergo continuous changes.

Comprehensive experimental studies carried out by McClung [8, 5], showed that dry snow exhibits dilatant strain-softening behaviour if shear deformation exceeds vertical deformation (settlement) due to the applied normal load. On the contrary, when vertical settlement exceeds shear deformation, snow shows a strain-hardening behaviour. These properties are particularly evident in the alpine snow, because of its high porosity, and are significantly rate-dependent. The strain-softening effects are lower in a compacted snow layer (produced by settlements and stiffening of the slab material with time, usually observed in newly fallen soft snow). Temperature also influences the constitutive behaviour of snow: increasing temperature increases creep rates. This phenomenon is pronounced near the melting point.

Two main modes of snow slab avalanches release are observed [5]: dry snow avalanches, the primary cause of which is the propagation of shear instability in the weak layer, and full depth avalanches, when the slip of the entire snow pack over the ground (gliding) occurs, due to an addition of free water in the snow pack that produces an unstable condition lubricating the interface of gliding. Tension cracks precede full depth avalanches formation.

Similarly to the instability in over consolidated clays [8], in dry alpine snow avalanches a shear failure (attainment of peak shear strength) occurs somewhere in the weak layer under high stress concentration (due to the contrast in material properties between the slab and the weak layer or to macroscopic imperfections). Due to the strain-softening behaviour, the peak shear strength drops to the residual value and the shear band slowly propagates until it reaches a critical length, as predicted by fracture mechanics [3]. From that moment the shear band propagates quickly until the collapse of the snow slab. The first observable fracture in connection with snow slab release is a tension crack propagating across the slope. This mechanism explains why a dry slab avalanche can release when a shear stress lower than the snow peak shear strength is applied and the delay between the instant

in which the external load is applied and the collapse. An increase of temperature could precipitate avalanche release as the creep rate increases.

If the added loading by new snowfall causes a shear stress approaching the snow peak shear strength in the weak layer, rapid shear fracture occurs in the layer and the collapse occurs suddenly. From the above it is clear that in order to understand the slab avalanches triggering and run out mechanisms, snow compressive, tension and shear strength, compressive and shear stress-strain response and fracture properties have to be known.

2.2 Shear strength

In order to understand the mechanical behaviour and the failure mechanisms of snow, reproducible experiments must be carried out in controlled conditions. Various studies on shear failure of snow samples under controlled laboratory conditions have been performed by a number of researchers. For example, McClung [7] used a simple shear test apparatus to test snow samples in plane strain conditions. A shear box was used, consisting of a fixed top cap and a bottom cap which moves in the horizontal direction at a constant rate. The snow sample, surrounded by a reinforced rubber membrane, has a diameter of 115 mm and is 16 to 18.5 mm thick. The sample is introduced into the box, a vertical load is applied to the top cap and kept constant during the test. The shear load is then applied to the lower cap at a constant displacement rate, in the range between 3.6×10^{-5} mm/s and 2.5×10^{-3} mm/s. Vertical displacement, horizontal displacement and applied horizontal load were recorded throughout the test. The results of the tests on specimens with low snow density showed that for slowest shear rates the shear strength increases continuously with shear displacement and vertical settlements occur. For faster shear rates a strain softening is observed with peak and residual shear strength values and dilatancy occurs before the peak is reached. Both peak and residual strength increase with applied normal stress.

Schweizer [12] carried out a number of shear tests on the refurbished shear test apparatus used by McClung. A normal load of 4.9 N was applied in all the tests, the strain rate varied between 7.6×10^{-6} s^{-1} and 5×10^{-3} s^{-1} and three different temperature values were used ($-5\,°$C, $-10\,°$C and $-15\,°$C). The results showed that for lower shear strain rates the snow shear stress-strain behaviour is ductile and the shear stiffness is lower. For faster strain rates the stress strain behaviour is brittle, the peak strength is lower and the shear stiffness increases. The ductile-brittle transition occurs at a strain rate value of about 1×10^{-3} s^{-1}. Both shear strength and stiffness increase when the temperature decreases.

Reiweger et al. [11] presented a new load-controlled laboratory shear test apparatus. The snow sample, which can be taken from the field or produced in the laboratory by a special snow machine and can be homogeneous (only one layer) or layered (three layers), is 0.2 m $\times 0.1$ m $\times 0.05$ m in size. It is placed between two sample holders and tilted by an angle α: the lower holder is fixed and the upper holder is free to move. The snow sample is then gradually loaded by increasing the weight on the upper sample holder, with a rate varying between 0.01 N/s and 3 N/s. The force acting on the sample and the displacement of the upper sample holder, in the slope parallel and slope normal direction, are measured. Particle image velocimetry was used to measure local displacements. An acoustic emissions measuring system was used to estimate microscopic failure before final fracture. The results showed a strain softening behaviour of snow and a concentration of deformation in the weaker layer.

The above-mentioned tests have been developed in order to study the mechanical behaviour of snow in controlled conditions. For this aim, they require sophisticated techniques of sampling and conservation of snow specimens until testing. On the other hand, some in-situ tests have been proposed to assess the stability of the snowpack with a simple and fast procedure, which gives some index of stability related to the snow shear strength.

The most widely used in situ shear test device is shown in Figure 1. This test allows to obtain the shear frame index of the weak layer of a snow pack. Typical frame used on a wide variety of alpine snow types has a section of 0.025 m^2. The frame index is influenced by the frame mass and loading rate [10]. In particular, the frame index increases with higher frame mass and lower loading rate. The shear index increases for lower temperature. Furthermore there is a good relationship between the density of the initially metamorphosed snow and the shear strength. It was also observed that the shear index is affected by the skill of the operator and the results of the tests have a high variance.

In order to study the scale effects on shear strength of snow, Perla et al. [10] performed some tests on alpine snow pack with a rotating shear vane apparatus. A large snow sample is collected in a cylindrical drum, with a diameter of 0.5 m, which contains a set of rigid vanes welded to the bottom half of the drum. The apparatus is then transported to a cold laboratory for the tests. The upper half drum is fixed while the bottom half can rotate with a constant angular speed of 0.05 rad/s. The tests results, compared with the results of shear frame tests performed on the same snow pack, showed that the sample size deeply influences the shear index. The shear index decreases with the increase of the tested section.

3 The new apparatus

3.1 Design objectives

The new apparatus has been designed to be light and simple enough to be employed in the field, yet maintaining the possibility of a complete control of the test as in a laboratory. All the components and subsystems must be able to fulfil their functions at low temperature, and to be easily operated in a snow pit on a slope.

Another intent of the new device is to reduce the errors that, using the shear frame described above, affect the estimation of the shear strength, induced by the manual application of the load. One of the main design specifications was to permit to apply the normal load, in order to simulate the weight of the snowpack above the layer to be sheared. Another important aspect of the apparatus is its capability to obtain a nearly undisturbed specimen of the snowpack containing the layer to be tested, i.e., the shear box itself, acts also as a sampler.

To fulfil the above-mentioned requirements, a twofold approach has been followed, to gather the advantages of the portable shear frame and those of the laboratory devices derived from the geotechnical field: from the former, the portability for in-situ testing on nearly undisturbed specimens lying on the layer of interest; from the latter, the exactly prescribed kinematics and a precisely controlled load history, with a continuous recording of the quantities of interest (force and displacement). Therefore, the apparatus described in this paper has been conceived as a compact, lightweight laboratory-type shear box, incorporating a sampler, usable also in the hostile alpine environment by a team of two operators.

The kinematic of the apparatus imposes a fracture of the specimen, and subsequent sliding of its upper half, along a pre-determined plane, so that the conditions of a *direct shear test* are attained [15, p. 127]. It is worth noting that this apparatus has been designed to impose that the fracture occurs in a particular shear plane that is the weak layer in a snowpack, despite the fact that the stress state on this plane is known in terms of resultant only.

On the basis of the above, the shear box has been designed to allow testing a snow sample with size similar to that of the manual shear frame. As regards to the stress exerted on the specimen, the maximum normal stress was chosen about 35 kPa, in excess of the pressure corresponding to a typical alpine snow cover, and the maximum shear stress was assumed to be around 30 kPa.

3.2 Mechanical design

The structure of the shear testing apparatus can be divided into two main parts (Figure 2):

(i) A fixed frame, which serves as a support for the moving part, holding also the measuring instruments.

(ii) A drawer-like part, which comprises the upper half of the snow specimen, the pneumatic actuator that produces the shear force, and an air chamber close by a rubber membrane that, when inflated, applies the normal pressure to the sample.

The two parts are connected through a couple of linear guides made of hard-anodized aluminium (Igus DryLin WSQ-10) with plastic low-friction sliding bearings, holder by chromate zinc die-cast supports. These elements are maintenance-free, and have been chosen because of their resistance to corrosion and dirt.

The lower half-box (9) (Figure 3) is welded to two couples of vertical U-shaped profiles 20 mm × 20 mm connected at the top by a transversal rectangular tubular profile 30 mm × 20 mm. These tubes are linked together, in the longitudinal direction, by a sturdy handle (1). The material used in all structural parts is steel, with thickness of 2 mm. This part of the apparatus has been designed as a support to guide the drawer during the shear test, and as a sampler to be pushed into the snow to form the specimen. The lower edges of the lower half-box are sharpened to help the penetration into the snow; two vertical blades (11), welded with a 2 mm clearance from the box, guide the bottom shovel (10) that closes the sampler. The specimen size is 160 mm × 160 mm × 80 mm so that the shear plane, located at mid-height, has an area of 256 cm², similar to the standard shear frame described previously [14].

The drawer is made of two main components: the top cap and the upper half-box. The top cap (6), is made of a plate of aluminium, 8 mm thick, carved for a depth of 2 mm to obtain the air chamber. This piece is clamped to the upper half-box (8), by means of tightening screws, holding in between the rubber membrane (7). The membrane is glued to the outer edges of the top cap to prevent gas leaking from the air chamber. The shear force is applied to the drawer by a pneumatic actuator (3), fixed on the top cap by means of two L-shaped supports, whose rod, in extension, pushes on the load transducer (2), fastened to the fixed frame.

To ensure the correct direction of penetration, the vertical U-shaped profiles contain also the guides for 4 carbon-fiber bars (12) to be pushed into the snow before sampling.

All the steel parts have been treated with phosphate conversion coating and painted, to protect the surfaces from oxidation and corrosion.

3.3 Pneumatic system

A schematic description of the pneumatic system is shown in Figure 4. Both normal and shear load are applied to the specimen by means of a pneumatic system. The gas source is a small disposable bottle (1) containing about 1 l of nitrogen (N_2) at 110 bar (11 MPa), usually employed in air-conditioning maintenance services. Through a primary pressure-reducing valve (2), the pressure in the circuit can be imposed in the range 0-10 bar (0-1 MPa). The circuit is made of polyamide tubes, with quick fittings.

The use of pneumatic actuators in the design has been chosen as a alternative to electric motors powered by batteries, which may suffer from low temperature in the field; moreover, this choice has been suggested by positive previous experience on direct shear testing on rock [1].

The normal force is applied by pressurising a chamber contained in the top cap of the specimen holder, closed by a rubber membrane in contact with the snow specimen. The shear force is generated by a pneumatic actuator (7). The actuator is a double-acting cylinder (Metal Work RNDC), with diameter $D = 32$ mm and stroke $S = 25$ mm, capable of developing a force, in extension, of about 400 N at 5 bar (500 kPa).

The test is carried out through the following main steps:

i. By means of the valve (6) the pressure in the top chamber (8) that applies the normal load to the specimen is set.

ii. The counter-pressure in the actuator is imposed by the valve (5) through software control and kept constant.

iii. The displacement of the upper half-box is obtained regulating the pressure in the actuator (7), by the valve (4) through software control.

The electronic system used to control the valves is described below.

The pressure transducer (9) measures the gas pressure in the top chamber. The pressure in the actuator is measured by a sensor built in the proportional valves (4) and (5).

3.4 Measuring instruments

The device is equipped with a force transducer HBM C2, with nominal load of 500 N, accuracy of 0.2 %, with degree of protection IP67 and operating temperature range $-30\,°C$ to $85\,°C$. The instrument is mounted on the fixed frame ((2) in Figure 3) such as the rod of the pneumatic actuator, during extension, pushes on it causing the movement of the top cap and of the upper half-box.

The displacement of the upper half-box is measured by means of a LVDT submersible transducer (RDP DCW1000B) with linear range of $±25$ mm, and operating temperature range $-50\,°C$ to $80\,°C$. The instrument ((4) in Figure 3) is clamped to the fixed frame and its armature is connected to the moving top cap ((6) in Figure 3).

The pressures in the top cap chamber and in the actuator are measured by means of a pressure transducer, as described above.

3.5 Control and acquisition system

The core of this subsystem is a controller (National Instruments CompactDAQ-9174), interfaced through separate modules, with the measuring instruments and with the proportional pressure control valves. This device has a $-20\,°C$ to $55\,°C$ operating temperature range, and has a maximum power consumption of 15 W, provided by a small battery pack at 24 V.

A portable computer which allows to run a control and visualization application, developed within the National Instrument LabView environment, integrates the acquisition system.

4 Test procedure

The first phase of the test procedure is the preparation of the snow sample.

The task of this phase is to include a specimen, with the layer of interest aligned with the prescribed shear surface: the apparatus works as a sampler. To this end, a procedure similar to that described by Sommerfeld [14] can be followed, and a plane parallel to the test layer, 4 cm above, is exposed. Then, the following steps are carried out:

(i) The upper half-box is blocked to prevent accidental movements and the directional bars are introduced into their guides (Figure 5(a)).

(ii) The shear box, without the bottom shovel, is laid on the snow surface, with its longitudinal axis parallel to the slope.

(iii) The directional bars ((12) in Figure 3) are pushed into the snowpack to fix the direction of penetration (Figure 5(b)).

(iv) The whole apparatus is pushed, through the handle ((1) in Figure 3) about 9 cm into the snow (Figure 5(c)).

(v) In front of the apparatus, the snow is removed for a depth of 8 cm, and the bottom shovel is slid into position, to cut the specimen from below (Figure 5(d)).

Now, the specimen is in place, and the test can be carried out. If necessary, the shear box can be lifted and placed on a horizontal table to perform the test.

The testing phase begins applying to the sample the normal load, inflating the air chamber to the requested gas pressure. The chosen pressure is imposed and kept constant by means of the regulator ((6) in Figure 4) while its value is read by the pressure transducer and displayed on the computer screen.

The shear phase starts with the pressurisation of the retraction chamber of the air actuator to a convenient pressure value: this value is maintained constant throughout the test. Subsequently, the extraction chamber is pressurised. The pressure is regulated by means of the proportional pressure control valve, which is controlled through the CompactDAQ device by a software that, based on the feedback from the load and displacement transducers, can be set up to perform in different operation modes. In the present version of the control software the device operates in load control with prescribed loading rates.

5 Preliminary tests

The new shear device has been subjected to a number of tests aimed at assessing its capabilities, before of its application in the field. A first series of experiments have been devoted to the evaluation of the friction forces developed at the guide support. For this purpose, a specific test procedure was devised in which the box was used upside down and, instead of the specimen, different weights were laid inside the top cap, on the rubber membrane.

In order to evaluate the shear force at incipient sliding it is necessary to choose a good estimation of the corresponding time. Let us consider Figure 6, in which two curves are plotted, showing the measures of shear displacement and force versus time, during a typical test conducted on an artificial material specimen (see below).

The displacement curve shows an abrupt change of slope around the time of incipient sliding. This time is found conducting the tangents to these two parts of the curve and finding their intersection. The shear force measured at the same time is assumed to be the shear force at first sliding.

The results of the shear tests on the guides show a linear relationship between normal and shear forces. Obviously, no results are available for normal forces below the weight of the upper half-box. As shown in Figure 7, the normal and shear forces divided by the nominal cross section area of the sample are plotted, to obtain, via a linear regression of the data, a corrective term, τ_g, to be subtracted from the shear stress measured during a shear test, at the corresponding normal pressure, σ_n. The corrective equation is

$$\tau_g = 0.107\sigma_n + 0.29 \quad \text{[kPa]}. \tag{1}$$

Another series of experiments have been devised to familiarise with the test procedures and to verify in the laboratory the capabilities of the apparatus to measure correctly the various quantities during a shear test. To this end, the measurement of the friction coefficient between two slabs of expanded polystyrene has been carried out with the apparatus.

Several specimens of expanded polystyrene (density $\rho = 20\,\text{kg/m}^3$) have been prepared by means of a hot-wire cutter, each one consisting in two parallelepipeds fitting exactly the two halves of the specimen chamber, taking care that their interface was aligned with the separation plane of the shear box. Shear tests have been performed on these specimens, applying a linear pressure ramp with a constant pressure rate, taking the specimen to sliding in a time ranging from 10 s to 20 s. A typical record of the test quantities is reported in Figure 6. Five tests have been performed at each level of normal loading, chosen to match the range of stress on the shear plane that is expected for snow samples in the field, namely, 0, 5, 10, 15, 20, 25, and 30 kPa. The maximum shear load measured during the test, corrected for friction of the guides as described above, has been used to evaluate the shear stress at incipient sliding. The results are plotted in Figure 8 together with the linear regression line, whose slope represents the angle of friction of the polystyrene slab. In particular, the friction angle determined with this procedure is $\phi_{\text{box}} = 33.1°$.

To confirm the validity of the results obtained with the new apparatus, i.e., the determination of the friction angle of the polystyrene slabs used in the preliminary testing described above, a number

of experiments have been performed with a tilt test table, where specimens identical to those used in the shear box, loaded with lead weights, have been inclined slowly up to the onset of sliding. The results of these tests (squares in Figure 8), agree fairly well with those obtained with the shear box (circles), and the linear regression gives a friction angle $\phi_{\text{tilt}} = 31.6°$, sufficiently close to the value ϕ_{box} given above.

These preliminary tests on polystyrene confirmed the effectiveness of the device. A campaign of tests preformed on snow samples both in-situ (in a new experimental site, see [4], [2]) and in cold laboratory is under way. The results will be ready as soon as their general validity is confirmed.

6 Conclusions

The new shear device has been calibrated in laboratory in the whole range of the design pressures. The tests on artificial samples have shown its capability of performing realistic direct shear tests. Thus, it is possible to assert that the mechanical design and the electronic control and measuring system are satisfactory.

Among the improvements that will be introduced, the adoption of a compact watertight case for the instrumentation will add portability and ease of usage to the new apparatus in the field. Moreover, to avoid some difficulties emerged in reading the screen of the inexpensive netbook PC used in the preliminary experiments in the bright daylight, a rugged PC with a transflective LCD appears highly recommendable.

A number of in-situ tests were also performed, in which the device worked well in the sampling phase, even if some difficulties have been pointed out in defining the correct orientation of the shear box with respect to the snow stratification. To obtain a good representative specimen, the operator must be able to individuate the layer to be tested prior to the sampling, and to execute carefully the steps of the sampling procedure in order to assure that the weak layer is positioned along the pre-defined shear plane.

From the first few experiments also emerged that, for certain snows, the rupture does not occur along the imposed shear plane. In this case, instead of a shear fracture separating the sample into two blocks sliding on a plane, a localized snow compaction is observed at the contact between the pushing wall of the upper half-box and the snow specimen. This is a symptom of an uneven distribution of the shear stress on the predefined shear plane. In order to minimize this problem and obtaining a more uniform stress profile, a system of blades similar to those present in the manual shear frame will be placed inside the upper half-box in a future improved version of the apparatus.

The new shear box described here will allow to perform systematic test campaigns to evaluate in the field the mechanical parameters of shear strength criteria for snow, with the ultimate goal of relating them to the environmental characteristics of the chosen site (e.g., temperature and snowfall history, snowpack depth, slope exposure etc.). The collected data will contribute to shed light on the mechanisms of avalanche triggering and to improve the forecasting of these hazardous natural events.

7 Acknowledgements

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Figure 1: The manual shear frame, hand driven by the operator through a force gauge
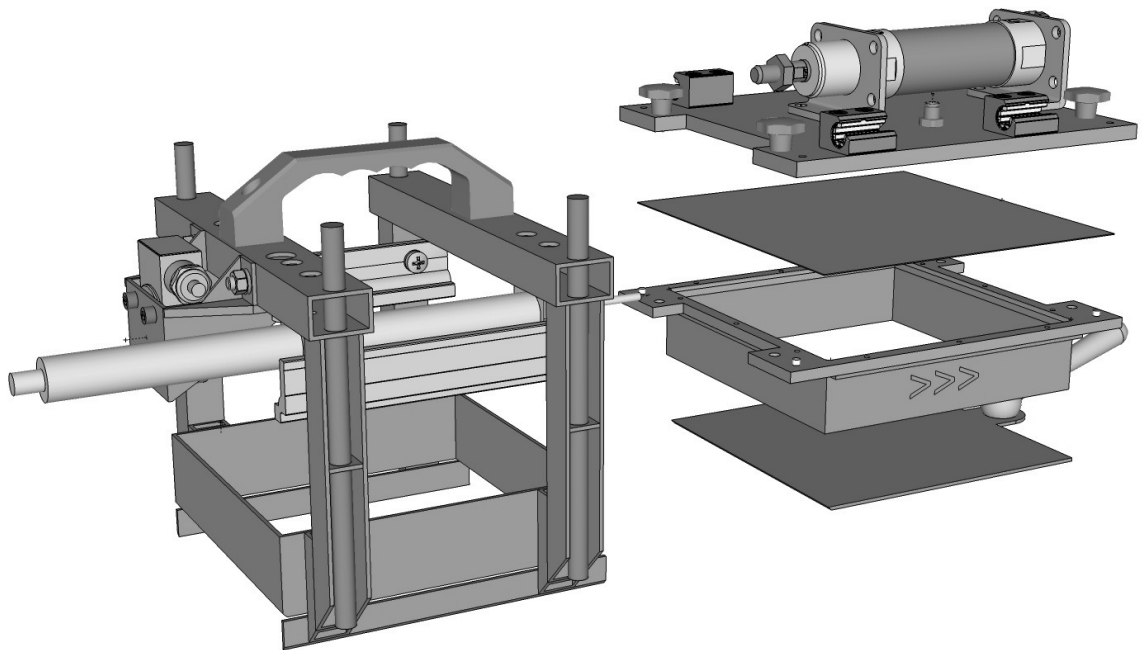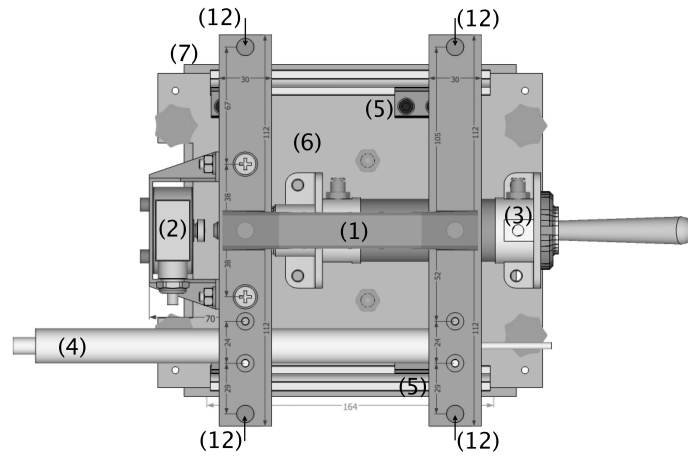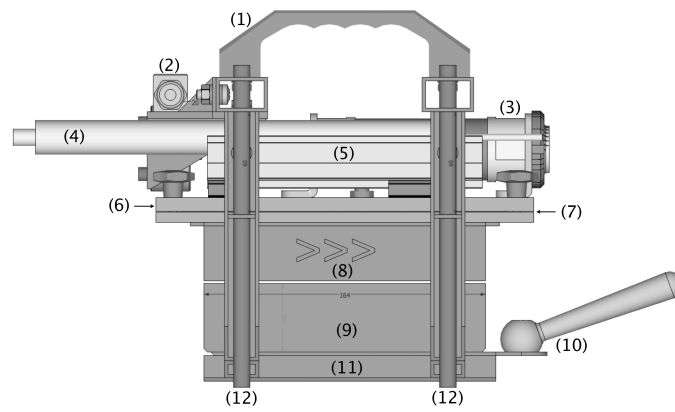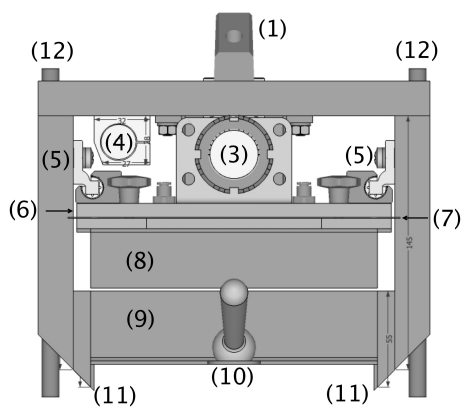

Figure 2: Exploded view of the main parts of the shear test apparatus. Left: fixed frame; right, from top to bottom: cap with pneumatic actuator, rubber membrane, upper half-box, bottom shovel

(a)

(b)

(c)

Figure 3: Top (a), side (b) and front (c) view of the direct shear testing machine, with a list of the main components. (1): handle, (2): load transducer, (3): pneumatic actuator, (4): displacement transducer, (5): horizontal guide, (6): top cap, (7): rubber membrane, (8): upper half-box, (9): lower half-box, (10): bottom shovel, (11): vertical blades, (12): directional bars.
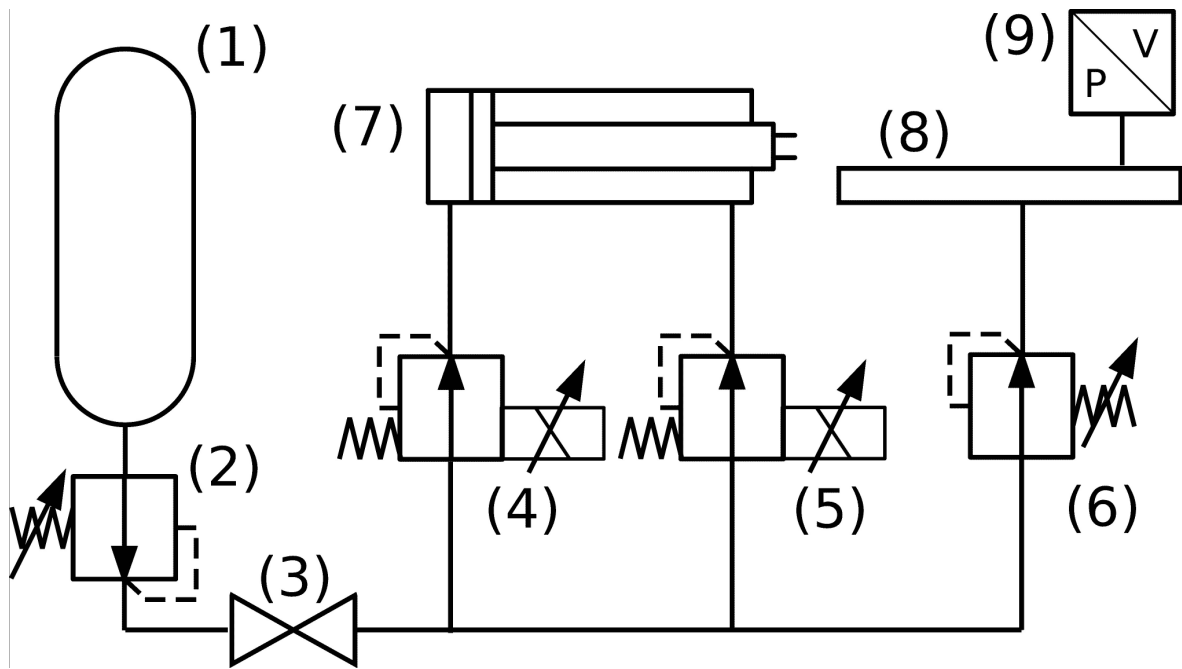
Figure 4: Schematic illustration of the pneumatic system. (1): nitrogen bottle, (2): pressure-reducing valve, (3): stop valve, (4): proportional electro-actuated pressure valve (extension force), (5): proportional electro-actuated pressure valve (retraction force), (6): adjustable pressure control valve (top chamber), (7): actuator (shear force), (8): top chamber (normal force), (9): pressure transducer.
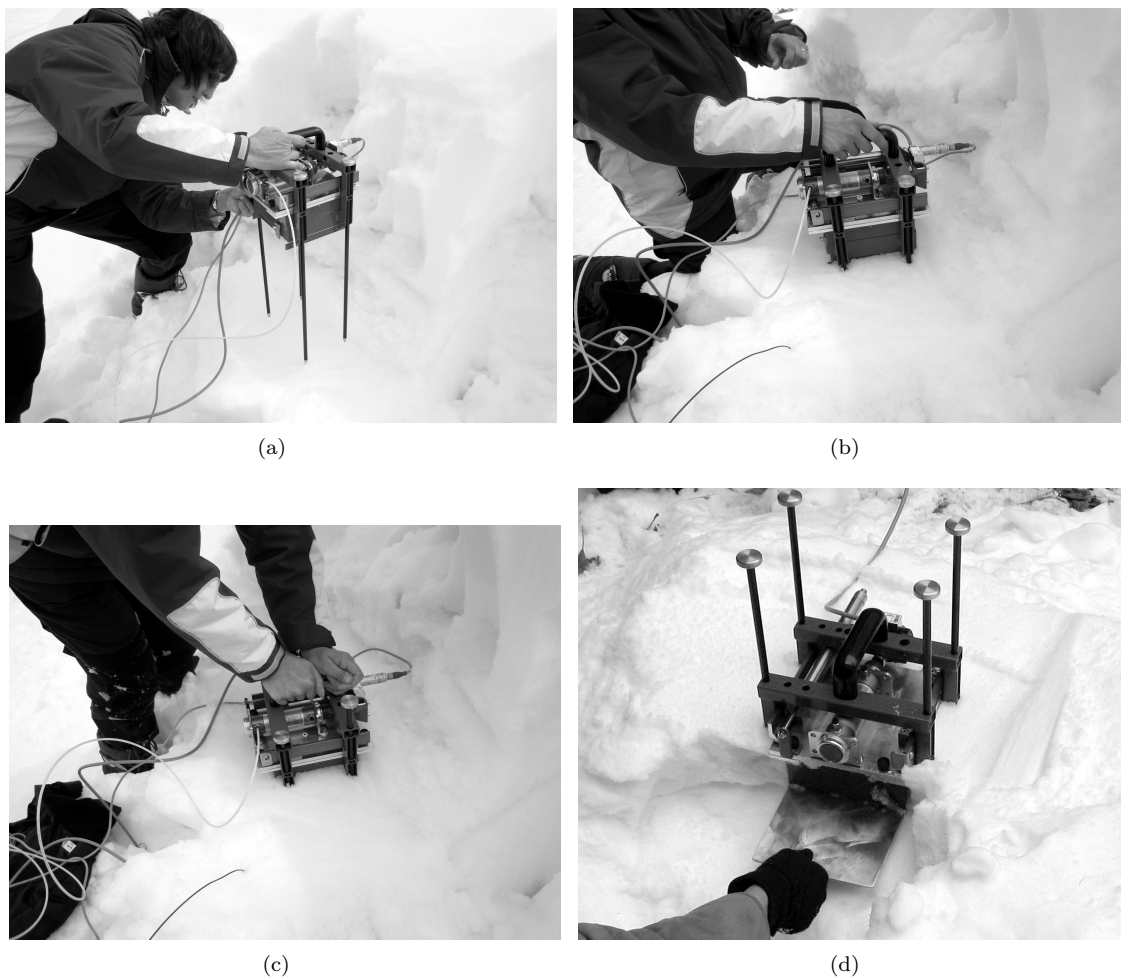

Figure 5: Sampling procedure: (a) the box with the directional bars is laid on the snow surface; (b) the directional bars are pushed into the snowpack; (c) the box is pushed to include the sample; (d) the bottom shovel is slid into position
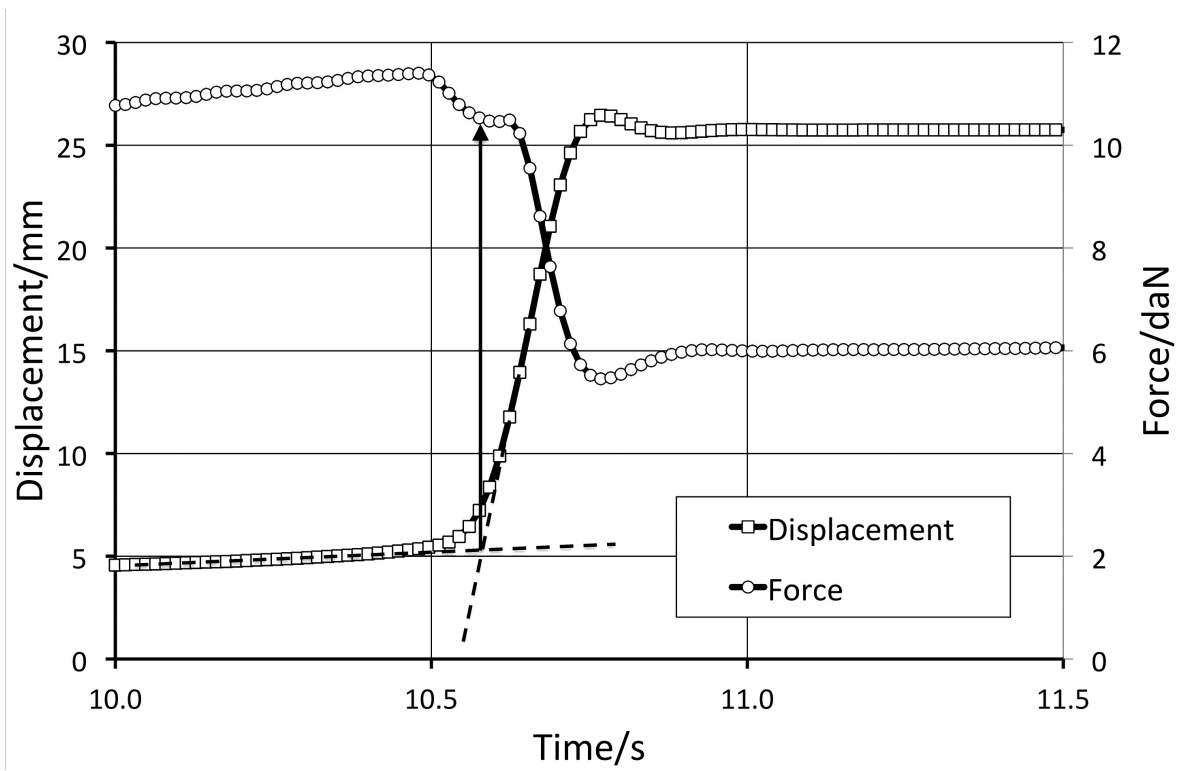
Figure 6: Example of the measurements during a shear test on polystyrene slabs. The dotted lines show the construction to find the time of first sliding and the arrow points to the corresponding shear force value
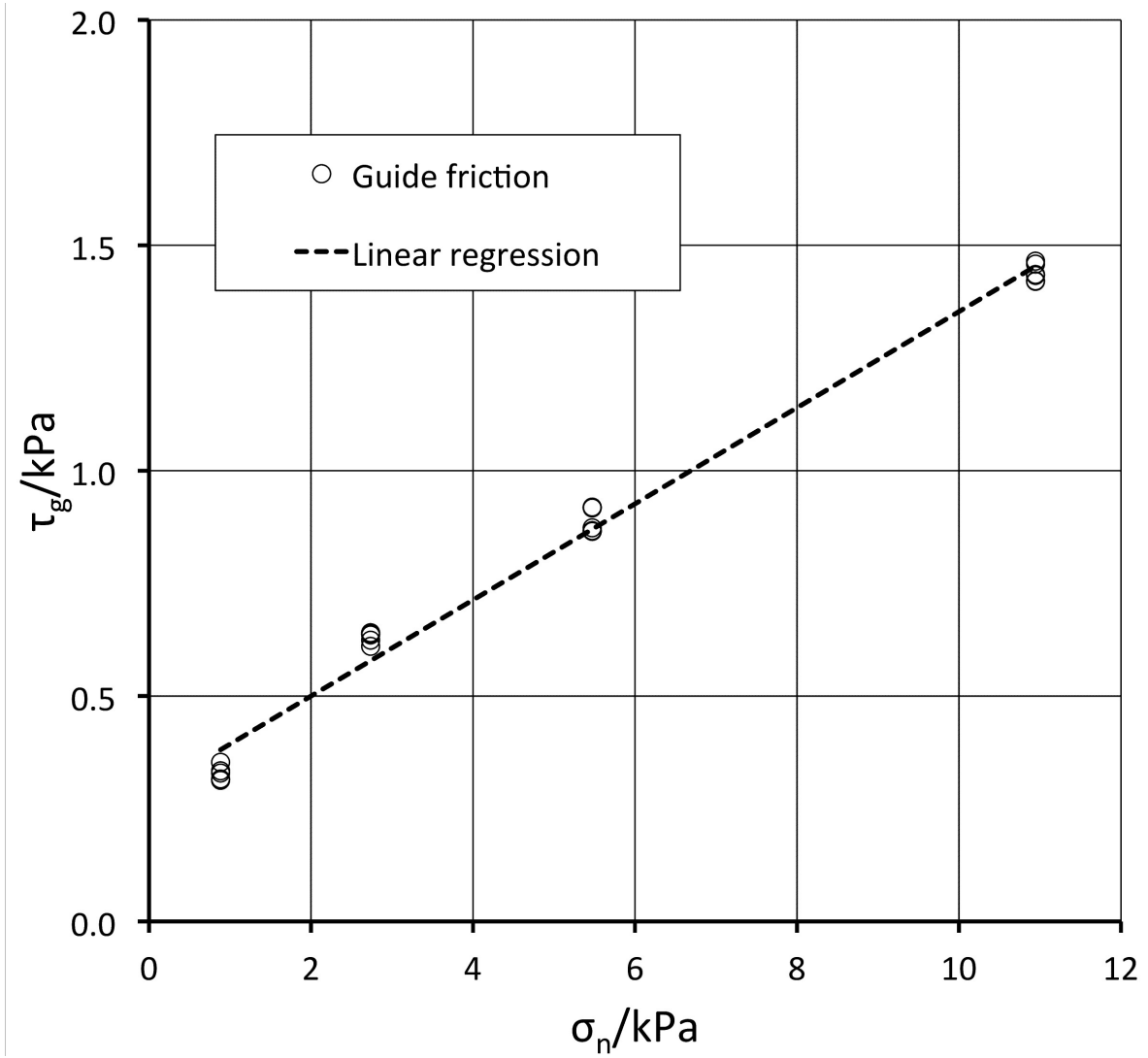
Figure 7: Measurements of friction of the guides of the shear apparatus and linear regression
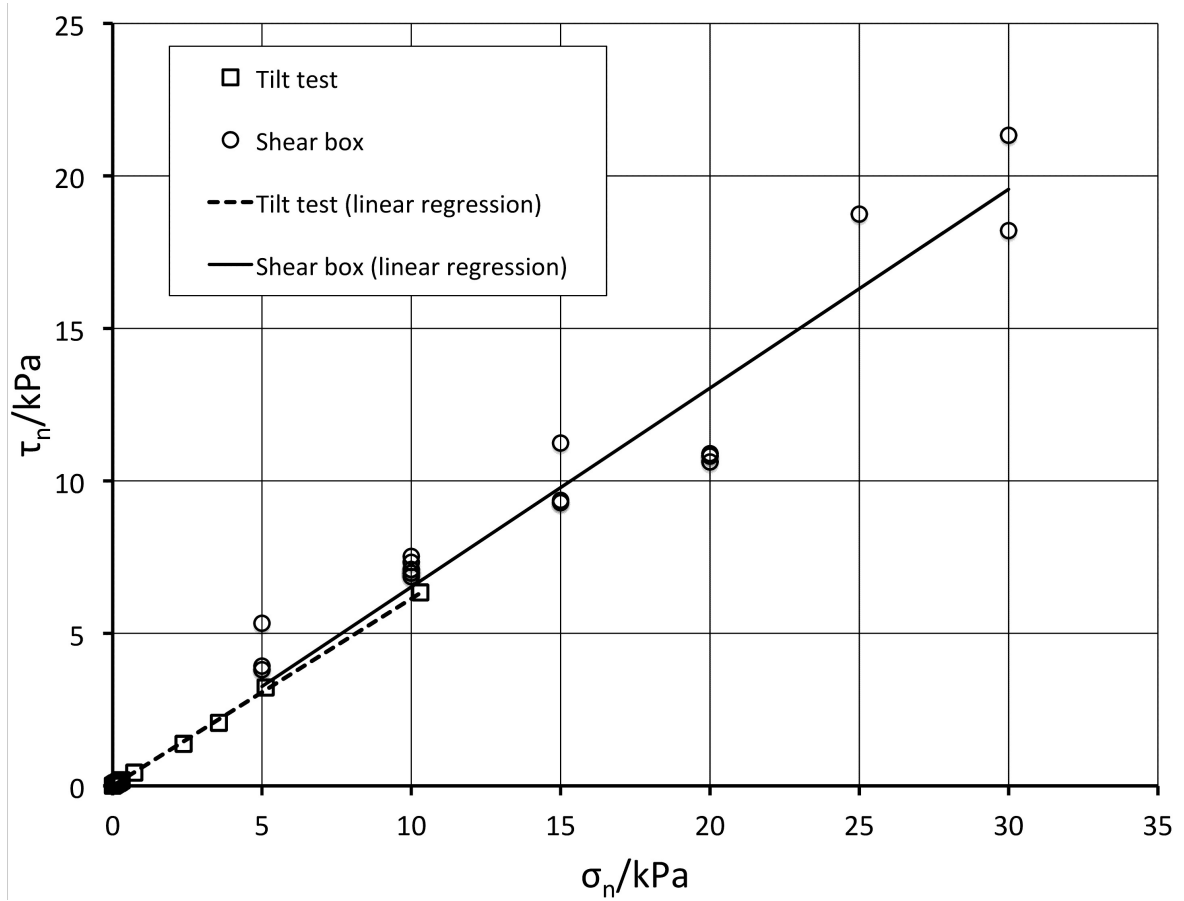
Figure 8: Shear vs normal stress at sliding onset for the polystyrene slabs. Two data sets are shown with their regression lines: from tilt tests (squares), and from the shear tests with the new apparatus (circles)