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# 1 **Experimental study of the shear strength of a snow-mortar** 2 **interface**

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12 **Abstract:** Within the wide field of snow mechanics the shear strength of snow is paramount. In the scientific literature a  
13 wide number of experimental and theoretical works exist with reference to the progressive shear failure of snow-snow  
14 interfaces under different conditions of internal and external actions. On the contrary, to our knowledge, few studies are  
15 devoted to the shear behaviour at the contact between a snow layer and a solid stiff material, although this topic could  
16 have various fields of application (e.g., glide avalanches, snow removal, snow-structure interaction, etc.). Here, we  
17 analyze results of experimental direct shear tests carried out in displacement control on a snow-mortar interface at given  
18 conditions of temperature and sintering times. We additionally use the Mohr-Coulomb failure criterion to represent shear  
19 strength along the interface both in failure and post-failure conditions.

20 **Keywords:** snow mechanics; snow friction; shear test; shear failure; Mohr-Coulomb criterion

## 21 **1 Introduction**

22 The shear strength and the related frictional behaviour of snow layers are topics of broad interest, both in  
23 the field of Civil and Environmental Engineering, with particular application to the field of snow avalanche  
24 forecasting and hazard assessment. Historically, such applications have been extensively studied (e.g., Casassa  
25 et al., 1991, 1989; Conway and Abrahamson., 1984; Gauthier et al., 2010; Gleason, 2002; McClung, 1977;  
26 Mellor, 1975). For instance, the shear strength of snow weak layers is fundamental to researchers' studies  
27 devoted to slab avalanche release and their triggering mechanisms (McClung, 1979; Mede et al., 2018;  
28 Podolskiy et al., 2014; Schweizer et al., 2003). Several of these authors have used experimental methods and  
29 have introduced devices specifically designed to perform direct and simple shear tests on snow samples mainly  
30 for understanding avalanche triggering mechanisms. For instance, Reiweger et al. (2009) designed a load-  
31 controlled apparatus to perform tilt tests on homogeneous and layered snow samples in a cold laboratory under

32 controlled conditions. Matsushita et al. (2012) developed a simple shear frame for assessing the influence of  
33 temperature and normal load in the shear resistance of artificial snow. Finally, Barbero et al. (2016) introduced  
34 a portable apparatus which was able to carry out direct shear tests on snow samples directly on-site. This latter  
35 device was used by De Biagi et al. (2019) to perform cold laboratory tests on reconstructed snow samples with  
36 artificial faceted snow layers.

37 Despite these studies on snow interfaces and shear strength, limited research can be found regarding the  
38 shear behaviour of a snow layer deposited onto a stiff material, e.g., rock or concrete. In general, some authors  
39 suggested that frictional behaviour of snow in contact with other materials could be investigated using ice  
40 instead of snow (Colbeck, 1994; Jellinek, 1960; Kietzig et al., 2010). This choice seems to be related to the  
41 greater repeatability of the mechanical properties that can be attained for a laboratory ice sample compared to  
42 those for a snow one. As a result, many problems concerning snow contact are faced with reference to ice,  
43 particularly in the field of winter sports and leisure activities (Kietzig et al., 2009). To our knowledge, only a  
44 few researchers have provided further indications on the shear behaviour at the snow-stiff solid material  
45 interface. For instance, Inoue and Honda (1955) carried out a series of contact tests on snow-solid interfaces using  
46 two different materials (glass and polytetrafluoroethylene). Their results show that snow adheres to the underneath  
47 material and this adhesion is dependent on the presence of a liquid water film at the interface. Inoue and Honda  
48 (1955) attempt to quantify the adhesion strength using the equivalent angle though no concrete conclusions could  
49 be drawn due to the limitations of the experimental device. Mellor (1975) provided a review of snow mechanics  
50 which included general information regarding snow adhesion and frictional behaviour in contact with solids.  
51 For example, he stated that the bond strength usually increases with decreasing temperature and varies with  
52 the surface properties of the solid material (i.e., roughness, hydrophobicity, etc.). More recently, McCallum  
53 (2014) examined friction between a stainless steel cone and polar snow, using the Mohr-Coulomb criterion, to  
54 interpret the results of CPT tests and quantify the compressive strength of snow. Heil et al. (2020)  
55 quantitatively measured the shear adhesion strength and surface energy of snow layer deposited on several  
56 solid surfaces (AL 6061, HDPE, stainless steel, and copper) with a non-destructive apparatus that accounted  
57 for the liquid water content at the interface. Jelle (2013) studied the problem of snow removal  
58 from photovoltaic modules and performed several experiments to determine the static and dynamic friction  
59 coefficients between snow and various roofing materials (glass, steel, bricks, polymers, concrete, and

60 bitumen). These tests were carried out using both a tension machine and a tailor-made friction table where the  
61 slip angle could be easily determined. The results show that during friction experiments snow slabs froze on  
62 the substrate surface because of the formation of adhesive forces (i.e., electromagnetic or electrostatic forces),  
63 which are strong enough even at inclination angles of about 90 degrees. Finally, Bartko and Baskaran (2018)  
64 investigated the problem of snow redistribution between building roofs by carrying out experimental tests  
65 using different commercial roofing materials.

66 This topic has many other applications, such as in the framework of glide avalanche release and evolution,  
67 the assessment of the basal friction and its reduction related to local failures of the snow-ground interface or  
68 to the presence of water films and moisture (Ancy and Bain, 2015; Mitterer and Schweizer, 2012; Puzrin et  
69 al., 2019). Another possible application is represented by slopes subjected to shallow landslides and reinforced  
70 by the application of shotcrete: when a slope with shotcrete reinforcement is covered by an intense snowfall,  
71 a snow avalanche can be triggered. Moreover, the comprehension of the shear mechanisms at the snow-solid  
72 material interface can aid some engineering problems such as that of thick snow slabs deposited on civil  
73 structures and infrastructures (roofs, walls, tunnels, bridges, etc.) or upon roads. In this latter case, the  
74 compaction of snow made by vehicles could influence the friction of the snow on the underlying road surface  
75 compromising traveler safety (Abele, 1963; Shapiro et al., 1997). Also, understanding snow-solid surface  
76 friction is critical for defining the power required for snowploughs or the effects of compaction of tyres on  
77 roads and airport runways (McCallum and White, 2016). Finally, especially in arctic environments, the design,  
78 construction and maintenance of snow runways need a better knowledge of this topic (White and McCallum,  
79 2018).

80 In this paper, we try to address this gap in knowledge by presenting the results of an experimental campaign  
81 carried out on 36 interface specimens made of a snow layer deposited and sintered over a cementitious mortar  
82 slab. Mortar was chosen as the stiff substrate because it possesses typical features of construction materials  
83 and, at the same time, some characteristics of natural materials (e.g., rock). The activity was performed with  
84 the portable direct shear test apparatus described by Barbero et al. (2016), modified in order to conduct tests  
85 in displacement-controlled mode (De Biagi et al., 2019a). Two sintering times and two testing temperatures  
86 were used in order to study their influence on the shear strength of the interface. The testing conditions were

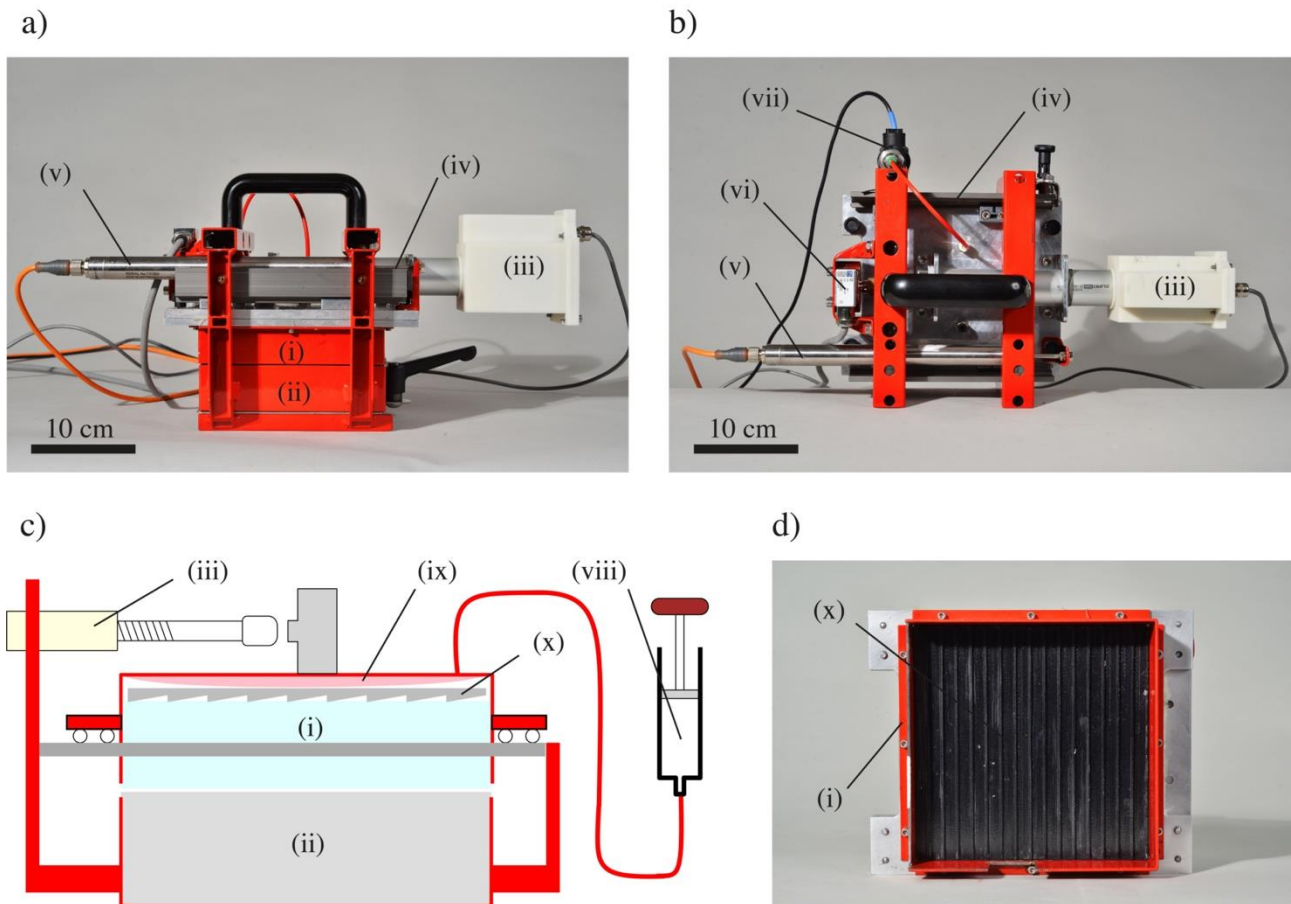
87 varied to reproduce conditions that could be potentially obtained on-site (e.g., temperatures, vertical loads,  
88 sintering and isothermal metamorphisms).

## 89 **2 Materials and methods**

90 The direct shear tests on snow-mortar interfaces were carried out in the framework of a scientific  
91 collaboration between Politecnico di Torino (Torino, Italy), and the Snow and Ice Research Center of the  
92 National Research Institute for Earth Science and Disaster Resilience, NIED (Nagaoka, Japan). The  
93 experimental activity was carried out in February 2019 in the cold laboratories of NIED (Nagaoka, Japan) at  
94 controlled conditions of temperature. All the experiments were performed with a displacement-controlled  
95 portable device for direct-shear tests, which is capable of applying adjustable normal pressure and  
96 displacement rates as previously developed by some of the authors (Barbero et al., 2016).

### 97 *2.1 The direct-shear test apparatus*

98 The test apparatus consists of a series of tools that can carry out direct shear tests without external aids (i.e.,  
99 no public electric power, pressurized-air system, etc.). This system was previously developed by Barbero et  
100 al. (2016) for on-site measurements of the mechanical characteristics of weak snow layers in avalanche release  
101 zones. The relatively small weight of the device (about 7 kg) and its compact power supply and control unit  
102 allow its operation in remote mountainous areas. In addition to this, the apparatus can be used to perform  
103 experimental activity in equipped laboratories such as in the case presented here.



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**Figure 1** a) and b) Lateral and top views of the testing device (shear box): (i) upper moving drawer (with upper part of the specimen), (ii) lower fixed drawer (with lower part of the specimen), (iii) stepper motor, (iv) sliding guides, (v) LVDT, (vi) load transducer, (vii) pressure transducer. The control system, (data logger) and the air portable reservoir are not shown; c) Sketch of the testing device cross section: nos. from (i) to (vii) are equal to the ones in sub-figures a) and b), (viii) external air reservoir, (ix) inner air chamber, (x) top cap of the moving drawer; d) Bottom view of the moving drawer in which is clearly visible the saw-tooth surface of the top cap.

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The main device of the apparatus is the “shear box” consisting of a steel frame (Figures 1a, 1b, and 1c) with a lower fixed and upper moving drawer. The inner part is empty and is able to host a specimen having dimensions 160 mm × 160 mm × 72 mm (length × width × height). Thus, the area subjected to shear stress is equal to 256 cm<sup>2</sup>.

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The lateral displacement, i.e., the shear displacement, is applied by a linear electric actuator with a motor controlled by an electric drive. The normal operational displacement rates are in the range of 1-100 mm min<sup>-1</sup>. The motion is constrained by a couple of linear guides made of hard-anodized aluminum (Igus DryLin WSQ-10) with plastic low-friction sliding bearings, held by chromate zinc die-cast supports.

120 The normal stress on the interface is applied through the inflation of a rubber square-shaped membrane in  
121 the higher part of the upper drawer (Figure 1c). A polymeric cap with saw-tooth surface (called “top cap”,  
122 hereafter), glued to the membrane, was installed in order to improve the transmission of the shear force applied  
123 during the test to the snow layer (Figure 1d). The membrane was pressurized through an external portable and  
124 manual control air reservoir, i.e., a gardener pump, with volume of 5 dm<sup>3</sup> and maximum pressure of 3 bars. A  
125 rectangular window (50 mm × 30 mm) is located on the side wall of the device allowing to directly observe  
126 the displacement field in the upper and lower part of the sample (De Biagi et al., 2019b).

127 During the execution of the tests, the apparatus measures the pressure in the air chamber, the relative  
128 displacements between the upper and lower part of the shear box, and the horizontal shear force by using a  
129 pressure gauge, a linear variable displacement transducer (LVDT) and a load transducer, respectively. A  
130 sampling rate of 2 kHz was adopted for all the acquired measures. The apparatus is interfaced through a  
131 National Instruments CompactDAQ control and acquisition unit, to a PC running a LabVIEW program, to  
132 control the testing parameters and to record all the experimental data over time.

## 133 2.2 *Snow-mortar samples*

134 The experimental tests were performed on artificially made samples consisting of two superimposed slabs  
135 (Figure 2a). The two different parts are briefly described in the following:

- 136 • the lower part is a square prism (160 × 160 × 40 mm<sup>3</sup>) made of cementitious mortar.
- 137 • the upper part is a square prism (160 × 160 × 32 mm<sup>3</sup>) made of artificially reconstituted snow.

138 In the following, the main phases of the specimen preparation are reported: all the phases were carried out  
139 in the NIED cold rooms and, at the end of the process, a snow-mortar interface specimen was ready for the  
140 execution of the direct shear test.

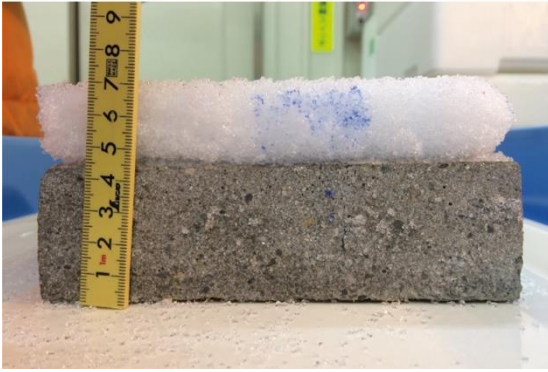
- 141 1. The snow was harvested outside the NIED laboratories and stored in the cold rooms of the research  
142 center (at a temperature of -10 °C) until the execution of the tests.
- 143 2. The mortar slab is placed on a table.
- 144 3. A two-part transparent mold is positioned around the mortar slab.
- 145 4. The snow was sieved to select only the grains with maximum size between 0.7 and 1.0 mm (Figure  
146 2b) and then immediately poured into the mold, over the mortar slab.

- 147 5. The height of the snow layer is kept higher than the final target (i.e., > 32 mm).
- 148 6. A vertical 100 N load is applied to the sample over a short period  $t_c = 5$  minutes (compaction phase,  
149 see Figure 3).
- 150 7. After the compaction the load is removed.
- 151 8. The mortar-snow specimen is left in the mold for the required sintering time  $t_s$  under isothermal  
152 conditions (sintering phase, see Section 2.3).
- 153 9. The upper part of the mold is removed.
- 154 10. The upper part of the snow sample was removed to reduce the height of the snow layer to the  
155 required value (i.e., 32 mm).
- 156 11. The bottom part of the mold is removed, and the snow-mortar sample is ready for the execution of  
157 the test.

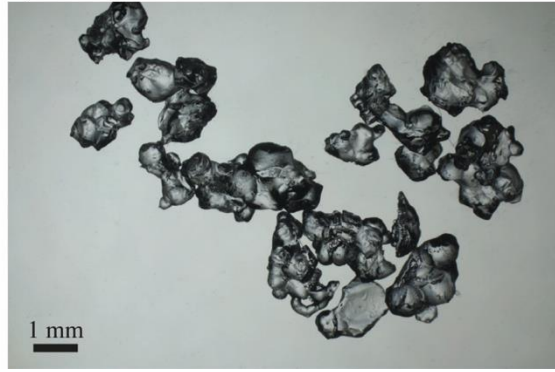
158 The grain size was chosen to represent the typical dimension of sintered hard slab snow that can be observed  
159 in nature (McClung and Schaerer, 2006). The final snow density was between 430 and 460 kg m<sup>-3</sup>. At the grain  
160 scale, the sintering process generated clearly visible necks (Figure 2b). Thus, according to the international  
161 morphological classification of seasonal snow (Fierz et al., 2009), the snow is identified as RG-lr. It should be  
162 noted that, in this work, the expression “sintering time” defines the time period ( $t_s$ ) experienced by each sample  
163 during which the isothermal sintering process (i.e., the creation and growth of bonds among grains) takes place.  
164 The snow hardness was measured using a push-pull gauge (model RZ-10, Aikoh Engineering) (Sugiura et al.,  
165 2011; Takeuchi et al., 1998).

166 A total number of nine mortar slabs were used to optimize the production of the specimens and the timing  
167 of the experimental activity. The characteristics of the snow and of the mortar are summarized in Table 1.

a)



b)



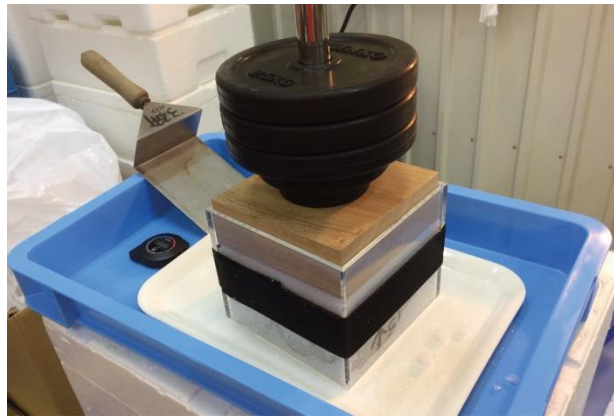
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**Figure 2** a) Example of a snow-mortar interface specimen; b) Micro-photo of the grains composing the upper half of the specimen. It can be clearly seen that single grains are connected by necks generated by snow metamorphism.



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**Figure 3** Compaction phase of the interface specimen under vertical load (100 N). The mold is of a prismatic shape with dimensions of (160 × 160 mm<sup>2</sup>) and is used for the snow specimens. The weight is set to impose a uniform and repeatable initial condition.

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**Table 1** Geometrical and physical characteristics of the different parts of the snow-mortar interface specimens. The heights of the two parts of the specimen are mean values and some variations can be observed among samples. More details for the hardness can be found in Sect. 2.3.

	Snow	Mortar
Density	445 ± 9 kg m <sup>-3</sup> (95%)	2 200 kg m <sup>-3</sup>
Snow Type	RG-lr	-
Snow grain size	0.7 – 1.0 mm	-
Snow hardness	One finger (1F), Four fingers (4F)	-
Basal area	Square, 160 × 160 mm <sup>2</sup>	Square, 160 × 160 mm <sup>2</sup>
Height	32 mm	40 mm

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180 2.3 Tests

181 The entire experimental activity was devoted to understanding the influence of both sintering time and  
182 temperature on the strength of snow-mortar interfaces. Thus, four combinations of different sintering times  
183 and temperatures were introduced, defining four groups of specimens code-named LS-T1, LS-T2, SS-T1, and  
184 SS-T2. LS and SS stand for long and short sintering time conditions, respectively, while T1 and T2 indicate  
185 the test temperatures of  $-10\text{ }^{\circ}\text{C}$  and  $-5\text{ }^{\circ}\text{C}$ , respectively. All samples were subjected to an initial compaction  
186 phase ( $t_c = 5$  minutes) under a vertical compressive load of about 100 N (producing a vertical stress 3.9 kPa)  
187 in order to generate a denser snow layer simulating dry hard snow slabs. Then, SS samples were obtained after  
188 a following sintering time ( $t_s$ ) shorter than 20 minutes, while, for LS samples,  $t_s$  was longer than 20 hours.

189 It can be observed that for LS-T1 and LS-T2 specimens the average hardness was 26.4 kPa and 16.9 kPa,  
190 respectively (see Table 1). These values were obtained with the micro-penetrometer and are comparable with  
191 the one-finger limit (1F) defined by the classical hand test (Höller and Fromm, 2010). SS-T1 and SS-T2 were  
192 tested with the same procedure, obtaining the average hardness values of 4.6 kPa and 4.1 kPa, both comparable  
193 to four fingers hardness (4F). This observation confirms that the specimen preparation procedure permits  
194 obtaining samples of different hardness depending on the sintering time and on the storage temperature.

195 In order to investigate the influence of the normal stress on the interface shear strength, three levels of  
196 normal stress were adopted: Low-Pressure (LP = 5.0 kPa), Medium-Pressure (MP = 7.5 kPa), and High-  
197 Pressure (HP = 10.0 kPa). These values were chosen to take into account the effects of different thicknesses  
198 of the snowpack that can potentially cover the interface. For instance, considering a snow density of  $450\text{ kg m}^{-3}$ ,  
199 the three levels LP, MP and HP are related to snowpack heights of 1.1 m, 1.7 m and 2.3 m, respectively.  
200 Three tests for each sintering, temperature and pressure combination were performed for a total number of 36  
201 direct shear tests.

202 Unfortunately, it was not possible to keep constant the normal stress during the execution of the test. This  
203 is due to several peculiarities of the shear apparatus:

- 204 1. The normal stress is applied by means of an inflated rubber membrane by using a portable hand-  
205 driven air pump that has to be controlled by an operator during the test. This method was adopted

206 because the shear apparatus is designed to perform on-site direct shear tests that have to be performed  
207 rapidly and with a light equipment;

208 2. The volume of the inflated rubber membrane is reduced. Thus, a small variation in its volume, due  
209 for example to rotations of the top snow surface, can cause a substantial variation of the air pressure  
210 transmitted to the snow-mortar sample.

211 Therefore, it is not possible to relate a unique value of the normal stress to each test as typically should  
212 occur during an ideal shear test in which the normal stress remains constant. Here, in comparison to other  
213 studies, the continuous monitoring and measurement of the air pressure in the membrane, and a careful and  
214 appropriate choice of the normal stress values to be used during the phase of result interpretation are necessary.

215 The main conditions characterizing the shear tests are reported in Table 2. The two testing temperatures  
216 were chosen to represent two different conditions of the snow, according to the available cold rooms of the  
217 NIED laboratory. Higher temperatures, near to 0 °C, that could be representative of a more realistic soil-snow  
218 interface were discarded in order to preserve the integrity of the snow part of the specimens from melting  
219 during the execution of the tests. The adopted displacement rate and maximum shear displacement had fixed  
220 values equal to 10 mm min<sup>-1</sup> and 20 mm, respectively. Particularly, these values were chosen to: i) take into  
221 account a mean shear rate among the ones usually used in many literature examples in which the mechanical  
222 behaviour of snow is studied (Matsushita et al., 2012; McClung, 1977; Puzrin et al., 2019; Reiweger et al.,  
223 2010), ii) catch and distinguish all loading, rupture and irreversible sliding phenomena occurring at the snow-  
224 mortar contact, and iii) neglect some undesired dynamic effects that can potentially compromise  
225 measurements. During the experimental activity the effect of velocity (i.e., displacement rate) was not  
226 investigated because the displacement rate was not changed.

227 **Table 2** Environmental and testing conditions during the experimental campaign.

Parameter	Value
Cold room temperature (T1, T2)	T1 = -10 °C, T2 = -5 °C
Maximum shear displacement range ( $u_{max}$ )	20 mm
Shear displacement rate ( $\dot{u}$ )	10 mm min <sup>-1</sup>
Average test time ( $t$ )	120 s

228 To document the progressive failure of the interfaces, the specimen was filmed during the test through the  
229 window located on the external side of the shear box with a high-speed video camera (Sony RX10-IV, 24-600  
230 mm lens) operating at 30 fps (RGB,  $3840 \times 2160$  pixels). The sensor was located at  $290 \pm 5.5$  mm from the  
231 sample surface and its plane was kept parallel to the lateral side of the target. Moreover, a lamp was used in  
232 order to obtain well defined videos. To enhance the contrast of the natural pattern of the snow sample surface,  
233 a blue nebulized ink was sprayed within the shear box window. Starting from these videos, each frame was  
234 extracted and stored as a black and white TIFF image file. Because it was not possible to trigger automatically  
235 both camera and testing apparatus, the synchronization of the video recordings with the physical measurements  
236 was obtained by comparing the displacement fields observed on the video frames and the ones measured  
237 through the LVDT. The beginning of the displacement in the video recording was determined by tracking  
238 marker points located on the shear box frame with the Digital Image Correlation technique (DIC, hereafter)  
239 implemented in the open source tool DICe (Turner et al., 2015). When the horizontal displacement measured  
240 with the DIC technique deviated from the null value, the corresponding frame was related to the same  
241 displacement value recorded by the LVDT.

#### 242 2.4 Preliminary data processing

243 The data (i.e., the “raw data”, hereafter) collected by the sensors underwent a correction procedure prior to  
244 analysis and interpretation. Besides the variability of the normal stresses, raw data are indeed considerably  
245 disturbed by other causes such as the electric-induced noise (related to the thermal motion of charges in electric  
246 circuits) and the random white noise affecting all the sensors output. The former is mainly related to the service  
247 frequency of the Japanese electric power distribution (i.e., 50 Hz, according to the Eastern Japanese standard)  
248 while the latter is generally due to the nominal measure range of the gauges. For instance, the pressure  
249 transducer has a range of measure from 0 to 50 kPa which is wider than the measured quantities (having a  
250 maximum of 10 kPa), so that the noise in pressure data is more evident than that existing in the other measured  
251 quantities (e.g., the displacement). Furthermore, another set of corrections is needed to consider the calibration  
252 of the quantities measured by the shear test system (i.e., the sliding guides friction, the air-pressure/normal-  
253 stress relation, and the progressive reduction of the contact area). The following data correction steps were  
254 employed:

- 255 1. Download of the raw data arrays (i.e., test time  $t$ , shear displacement  $u$ , air pressure  $p$ , and shear force  
 256  $T$ ) from the acquisition/control system. The sampling rate is the same for every array (i.e.,  $f_0 = 2$   
 257 kHz). An example of the original raw data collected by the transducers is presented in Figure 4a.  
 258 2. Execution of the Short-Time Fourier Transform (STFT) (Portnoff, 1980) and the following Low-  
 259 Pass Filter (50 Hz threshold) on the raw data to remove the electric-induced noise. Then, a moving  
 260 average of the data, with a computational window width of 0.25 s, was carried out to reduce the  
 261 residual white noise. Resampled data obtained via this procedure were used in the following  
 262 operations.  
 263 3. Computation of the corrected normal stress  $\sigma_c$  starting from the air pressure  $p$ :

$$\sigma_c = \frac{kp}{R} \quad (1)$$

264  
 265 where:  $k = 0.797$  is a coefficient, experimentally determined, which relates the imposed pressure  
 266 in the air chamber  $p$  to the normal stress  $\sigma_c$  acting on the sample in the initial conditions of zero shear  
 267 displacement and takes into account the incomplete contact and friction;  $R = \frac{A_c}{A_n} = 1 - \frac{u}{d}$  is the ratio  
 268 between the reduced contact area  $A_c$ , for a certain lateral displacement  $u$ , and the nominal area  $A_n =$   
 269  $d^2$ , and  $d = 160$  mm is the length of the lateral side of the square sample.

- 270 4. Evaluation of the friction force  $T_g$ , acting on the sliding guides, which reduces the actual shear load  
 271 transmitted to the specimen. The following equation (determined experimentally) was used:

$$T_g = \mu_d N_c + T_0 \quad (2)$$

272  
 273 where  $N_c$  is the corrected normal force defined as  $N_c = \sigma_c A_c$ ,  $\mu_d = 0.053$  is the dynamic friction  
 274 coefficient and  $T_0 = 1.373$  N. The friction force is, in general, influenced by the displacement rate,  
 275 which has been set to  $10 \text{ mm min}^{-1}$  in all the tests presented here.

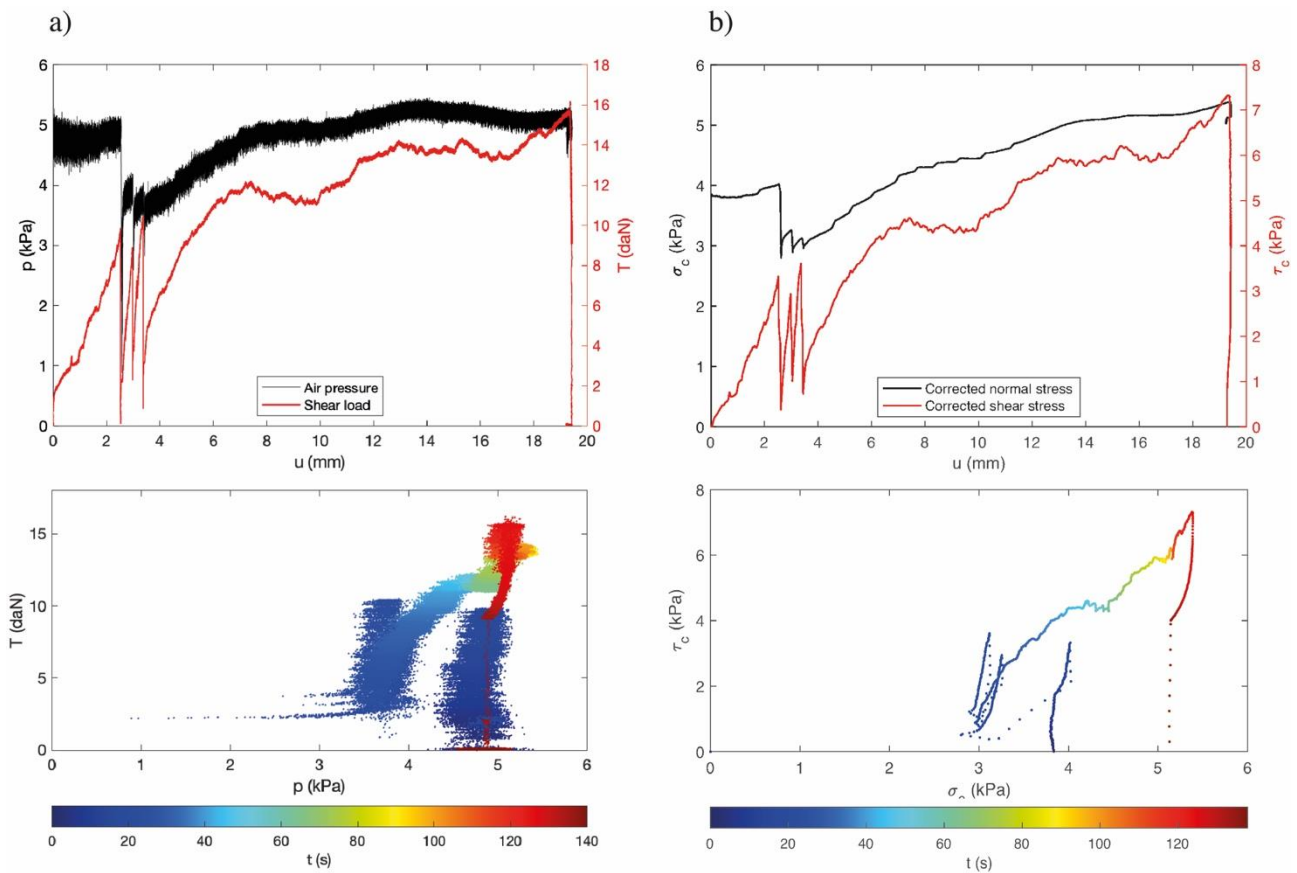
- 276 5. Determination of the corrected shear stress  $\tau_c$  with the following relation:

$$\tau_c = \frac{T - T_g}{A_c} = \frac{T - T_g}{RA_n} \quad (3)$$

277  
 278 in which  $T$  is the shear force measured by the load transducer.

279 6. Re-sampling operation (with a frequency  $f_1 = 40$  Hz) of the corrected data to reduce the  
 280 computational effort and the size of the output files without loss of information.

281 In Figure 4b, the corrected data referred to the LS-T1 test no. 1 are reported. All the above-described steps  
 282 were performed on each test in order to obtain a corrected set of data. The cleaning operation was performed  
 283 on all the sensor raw data, while the correction formulae in Eqns. (1) and (3) were implemented only for normal  
 284 and shear stresses. In practice, applying Eqns. (1) and (3) to raw data means deforming their graphs in some  
 285 way: during the first part of the test, the applied corrections reduce the normal and shear stress values while  
 286 the contrary happens in the second part. This is due to the progressive reduction of the contact area, related to  
 287 the nature of the considered tests.



288  
 289 **Figure 4** Comparison between raw and corrected data with reference to test LS-T1 no. 1: a) Raw data  
 290 recorded by the acquisitions system. In the upper plots, it can be seen the considerable variability and the  
 291 random noise that affect the pressure signal. In the lower graphs the same data are plotted in the  $\sigma - \tau$  plane  
 292 with a colormap highlighting the evolution in time of the data; b) Corrected data obtained by the application  
 293 of Eqn. (1) and (3).

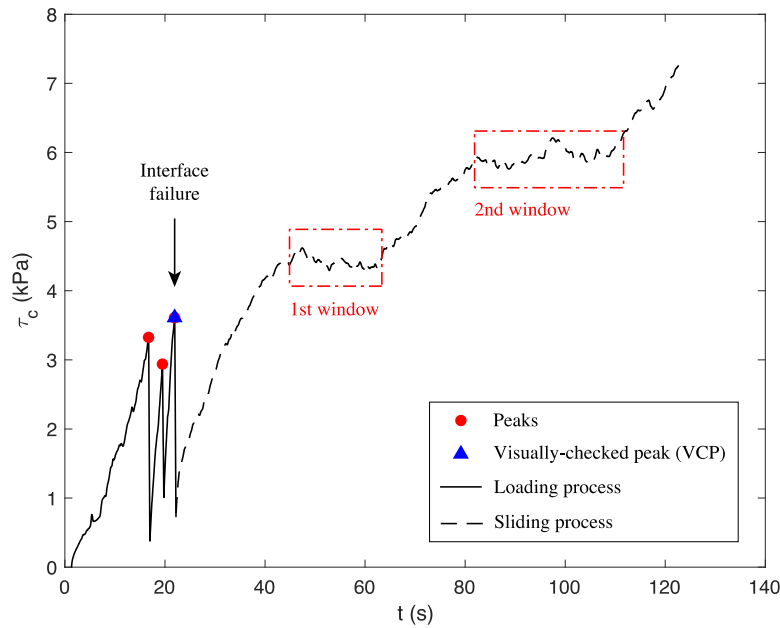
## 294 3 Results

### 295 3.1 Generality

296 The results of a typical snow-mortar direct shear test are shown in Figure 5 with reference to LS-T1 test  
297 no. 1 and its shear stress evolution in time. In almost all tests, two processes can be clearly observed: i) an  
298 initial *loading process*, and ii) a following macroscopic *sliding process*. Similar curves can be found in  
299 literature for stainless steel-snow shear strength (McCallum and Wiegand, 2018). During the former process,  
300 the horizontal applied load was gradually transferred to the snow-mortar interface until the detachment of the  
301 snow layer from the mortar slab occurs. The progressive damage of the snow-mortar interface is a complex  
302 phenomenon that involves the whole loading process. In this work, the *interface failure* (Figure 5) is defined  
303 as the definitive instantaneous rupture of the snow-mortar surface bonds that promotes the detachment of the  
304 snow layer from the underneath mortar slab and the beginning of the irreversible macroscopic sliding. In the  
305 loading process a certain number of peaks can be clearly observed in  $\tau - t$  graphs (Figure 5) that can be related  
306 to local rupture of the snow-mortar surface. Then, during the second process (i.e., the sliding one), the snow  
307 half of the sample macroscopically slides over the mortar slab and the relative shear displacement develops  
308 irreversibly until the maximum displacement  $u_{max} = 20$  mm is reached (i.e., the end of the test).

309 Referring to the loading process, each shear stress peak was followed by an instantaneous drop of both  
310 shear and normal stresses. Typically, the last one was related to the failure of the interface (i.e., the detachment  
311 of the snow layer from the mortar block). In 90% of cases, samples failed before reaching a displacement of  
312 4.80 mm (median value: 2.84 mm, mean value: 2.89 mm, standard deviation: 1.88 mm). More details can be  
313 found in Table 3 by considering separately the four classes of specimens. With reference to the average  
314 standard deviation values, all the LS specimens (i.e., both LS-T1 and LS-T2) and the SS-T2 ones seem to be  
315 less scattered than the SS-T1 samples. From test video recordings, it is observed that SS-T1 specimens are the  
316 least bonded, as they have undergone the shorter sintering time and have been subjected to the lower  
317 temperature. Both these aspects (shorter sintering time and lower temperature) can justify the behaviour of the  
318 SS-T1 group of tests, the great variability that characterizes their results, and the large value of the standard  
319 deviation. SS specimens (i.e., both SS-T1 and SS-T2) generally reached larger displacements before failing.  
320 Otherwise, LS specimens failed before the SS ones, for both temperatures, and show less variability in the

321 results. In fact, LS specimens were the hardest ones and once failed they behaved very similarly to a hard snow  
 322 slab sliding rigidly over the stiff substrate.



323

324 **Figure 5** Example of the typical results for shear tests on snow-mortar interface: loading and sliding  
 325 processes for the LS-T1 test no.1. The black solid line depicts the behaviour of the interface during the  
 326 loading process, while the dotted one shows the sliding one. Three peaks are identified with the red dots  
 327 and the blue triangle. The latter one stands for the visually checked peak (VCP). In the sliding process, the  
 328 two observation windows are identified by red rectangles. The data obtained for these windows are: for the  
 329 1st window, mean normal stress  $\bar{\sigma}_1^{LS-T1\_no1} = 4.34$  kPa, mean shear stress  $\bar{\tau}_1^{LS-T1\_no1} = 4.41$  kPa,  
 330 window time length  $WT_1 = 18.6$  s, standard deviation of the normal stress  $SD_\sigma = 0.09$  kPa; for the 2nd  
 331 window:  $\bar{\sigma}_2^{LS-T1\_no1} = 5.11$  kPa, mean shear stress  $\bar{\tau}_2^{LS-T1\_no1} = 5.94$  kPa, window time length  $WT_2 =$   
 332  $29.2$  s, standard deviation of the normal stress  $SD_\sigma = 0.06$  kPa.

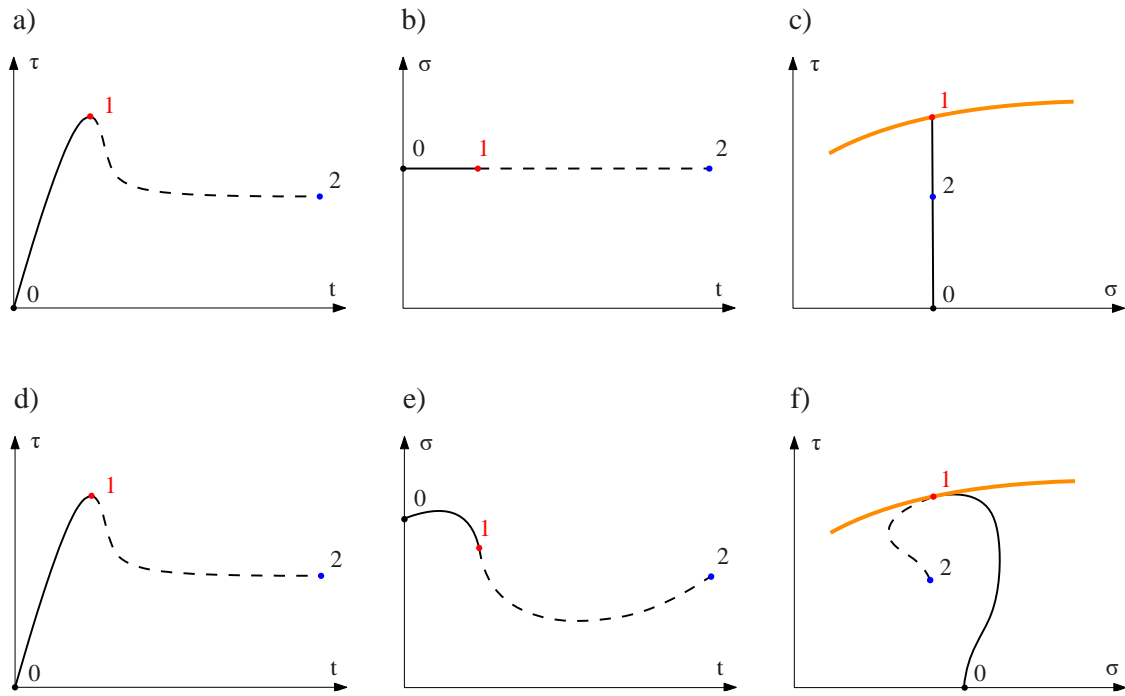
333 **Table 3** Values of the time at failure and relative horizontal displacement at failure for the four types of  
 334 specimens LS-T1, LS-T2, SS-T1, and SS-T2. The number of usable samples for each specimen type ( $n$ ) is  
 335 reported in the second column.  $n$  is the number of test (on a maximum of 9) that were successfully carried  
 336 out during the experimental campaign.

Specimens	$n$	Relative horizontal displacement at failure	
		Mean value (mm)	Standard deviation (mm)
LS-T1	6	2.62	1.06
LS-T2	6	1.83	1.29
SS-T1	5	3.46	2.86
SS-T2	5	4.22	1.28

337 After the first process, the slide occurred at the prescribed displacement rate  $\dot{u}$  until the achievement of the  
338 maximum horizontal displacement (i.e., 20 mm). However, the normal stress  $\sigma_c$  varied during the sliding  
339 process and its standard deviation was greater than 0.4 kPa in 90% of the tested specimens (median value: 0.64  
340 kPa, mean value: 0.61 kPa). Generally, the variability of the normal stress is uniformly distributed over all the  
341 specimens. Further, the average values of these standard deviations were computed for each specimen,  
342 providing the following results: 0.62, 0.62, 0.65, and 0.61 kPa for LS-T1, LS-T2, SS-T1, and SS-T2,  
343 respectively. The results are quite similar, showing that the variability of the normal stress is common for all  
344 specimens and does not depend on the sample characteristics.

### 345 3.2 *Typical results of the snow-mortar shear tests*

346 The variability of the normal stress during the tests caused some modifications also in the output graphics  
347 and in the following interpretation of the results. Typically, the output of a direct displacement-controlled shear  
348 test for which normal stress is ideally constant and represented by a simple stress path like Figure 6a. In the  
349  $\tau - t$  plane a loading process (point 1) and a sliding process with nearly constant  $\tau$  (point 2) can be easily  
350 observed, while, in the  $\sigma - \tau$  plane, the behaviour is represented by a vertical spike having the maximum at  
351 point 1, generally corresponding to the failure envelope of the interface (orange line in Figure 6a). Otherwise,  
352 when the normal stress is not constant in time, the stress path is quite disturbed and deviates from the previous  
353 vertical trend because of the variability of  $\sigma$  in time (Figure 6b). Thus, when the normal stress is constant in  
354 time, it is not necessary to study the entire stress history but only two points are sufficient to represent the  
355 resistance behaviour. On the contrary, when the normal stress varies, the entire stress path is useful to  
356 investigate the mutual relationships between normal and shear stresses. In this case, several different  
357 behaviours could be observed at different levels of  $\sigma$ , even within a single shear test. For these reasons, in the  
358 present work the entire stress path was taken into account to interpret the experimental results.



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**Figure 6** From a) to c), sketches of the typical output of an ideal displacement-controlled direct shear test with constant normal stress  $\sigma$ : a) In the  $t - \tau$  plane a clear peak (point 1) can be observed with reference to the failure of the sample. This is followed by a quick decrease of the shear stress, during the sliding process, to a constant value (point 2); b) All processes occur at constant normal stress; c) The stress path  $\sigma - \tau$  is a vertical spike reaching the failure envelope (orange line). Notice that the sliding behaviour (dashed line) from point 1 to 2 is hidden by the 0-1 segment. From d) to f), sketches of the typical output of a displacement-controlled direct shear test with variable  $\sigma$ : d) In the  $t - \tau$  plane the shape of the curve does not change considerably; e) The variability of the normal stress over time varies with sinusoidal-like shape; f) The stress path  $\sigma - \tau$  follows the variability of normal stress in time.

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### 3.3 Operations on the corrected data

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Starting from the data corrected following the procedure reported in Sect. 2.4 and considering the main results, the following framework was adopted for the interpretation of the measurements. The data were sorted into the four specimen types (i.e., nine samples for each specimen) previously defined in Sect. 2.3. Within each specimen type a different procedure was applied for loading and sliding processes.

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#### 3.3.1 Loading process

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In the loading process, the two corrected stresses were plotted with respect to time. For each test  $i$ , a certain number  $j$  of peaks was identified in the  $\tau - t$  plane by using a specifically developed automatic MATLAB script. Then, the peak shear stresses ( $\tau_{p,j}^i$ ) and the correspondent peak normal stresses ( $\sigma_{p,j}^i$ ) were identified. As an example, the peaks related to the first LS-T1 test are highlighted in Figure 5. The behaviour of the

379 specimen at any peak condition was checked against the video recording of the event to get further information  
380 on the nature of the observed phenomenon, particularly to verify if the loss of strength could be related to the  
381 detachment of the snow layer from the mortar surface and the beginning of the sliding process. To this purpose,  
382 a Digital Image Correlation (DIC) analysis was performed on the relevant video frames. These peaks, named  
383 Visually Checked Peaks (VCP in the following), allowed identification of a single pair of peak stresses for  
384 each test:  $\sigma_{VCP}^i$ , and  $\tau_{VCP}^i$ . The values of these loading stresses (i.e., stresses at failure) for all tests can be found  
385 in Appendix A. These stresses are the only ones that are surely related to the detachment of the snow layer  
386 from the mortar (i.e., the failure of the interface). The other peaks may refer to other, unobservable, phenomena  
387 such as: fracture of the snow layer, lateral compression of the sample, failures on the snow-mortar interface  
388 that could not directly be observed by the video camera, etc. Thus, only VCPs will be taken into account to  
389 discuss our experimental results. Finally, for each specimen, the  $\sigma_{VCP}^i - \tau_{VCP}^i$  pairs were fitted by using the  
390 following two linear equations, in order to identify the best fitting law:

$$\tau = a\sigma + b \quad (4_i)$$

$$\tau = a\sigma \quad (4_{ii})$$

391  
392 where  $a$  and  $b$  are two fitting parameters, which were determined with the Nonlinear Least Squares (NLS)  
393 method implemented in a MATLAB script (see Sect. 4). The results of the fitting operations for the loading  
394 process are reported in Table 4. It can be seen that the values of  $a$  and  $b$  are comparable between the two  
395 proposed fitting laws because of the small values assumed by parameter  $b$  in most cases. The one-parameter  
396 values derived from Eqn. (4<sub>ii</sub>) seem more reliable than those obtained via the two-parameters Eqn. (4<sub>i</sub>). This is  
397 related to two main reasons: i) the one-parameter law provided the highest coefficients of determination ( $R^2$ )  
398 for all the specimens (especially for SS-T1 specimens), ii) in case of SS-T1 specimens, the two-parameters  
399 law resulted in almost nil  $R^2$  because of the low reliability of VCPs data. The results of SS-T1 specimens were  
400 compromised by the partial collapse of the snow layer that occurs at the beginning of some tests (especially  
401 for low normal stresses). With the aim to partially solve the limitation of SS-T1 data, all the available peaks  
402 were considered in the fitting process through the one-parameter law. Finally, the italicized values (i.e., one-  
403 parameter values) in Table 4 are those selected to characterize the interface strength (see Sect. 4).

404 **Table 4** Fitting parameters obtained with Eqns. (4<sub>i</sub>) and (4<sub>ii</sub>) for all specimen types during the loading  
 405 process. All the values were computed on the basis of VCPs except for the star value (SS-T1 type) where  
 406 the fitting operation was carried out on the basis of all the visualized peaks, in order to have more data. The  
 407 values highlighted in italics are those selected to characterize the interface strength.

Specimens	Eqn. (4 <sub>i</sub> ) – two-parameters			Eqn. (4 <sub>ii</sub> ) – one-parameter	
	<i>a</i> (-)	<i>b</i> (kPa)	<i>R</i> <sup>2</sup> (-)	<i>a</i> (-)	<i>R</i> <sup>2</sup> (-)
LS-T1	0.947	-0.13	0.761	<i>0.927</i>	<i>0.760</i>
LS-T2	0.807	0.18	0.545	<i>0.833</i>	<i>0.544</i>
SS-T1	-0.051	4.60	0.020	<i>0.622 (*)</i>	<i>0.724 (*)</i>
SS-T2	0.523	0.21	0.685	<i>0.561</i>	<i>0.681</i>

### 408 3.3.2 Sliding process

409 For the sliding process, a different approach was adopted. First of all, for each test, the sliding process data  
 410 was isolated from the rest of the data. Then, two temporal windows were identified for each test by observing  
 411 the evolution of the two stress components over time. The windows had to satisfy three requirements: i) within  
 412 the windows, the sliding of the snow layer has to be evident, ii) each window has to span more than 10 s  
 413 (*WT* > 10 s) in order to be representative of the sliding process, and iii) the standard deviation of the normal  
 414 stress (*SD*<sub>σ</sub>) has to be smaller than 0.1 kPa, to reduce the variability of the data. These conditions are needed  
 415 to identify portions of sliding process in which the normal stress remains almost constant for a sufficient period  
 416 of time. Then, for the *i*-th test and the *j*-th window (with *j* = 1,2), the average values of the normal stress ( $\bar{\sigma}_j^i$ )  
 417 and of the shear stress ( $\bar{\tau}_j^i$ ) were computed (Figure 5). The values of these “sliding stresses” for all tests can be  
 418 found in Appendix A. Finally, the so obtained two  $\bar{\sigma}_j^i - \bar{\tau}_j^i$  pairs were linearly fitted following the Eqns. (4<sub>i</sub>)  
 419 and (4<sub>ii</sub>). Also, in this case, the above-mentioned procedure was applied to all specimens and the highest  
 420 coefficients of determination are those obtained with the two-parameters fitting described by Eqn. (4<sub>i</sub>). The  
 421 results of the fitting operations for the sliding process are reported in Table 5 where the italicized values (i.e.,  
 422 two-parameters values) are those selected to characterize the interface strength (see Sect. 4).

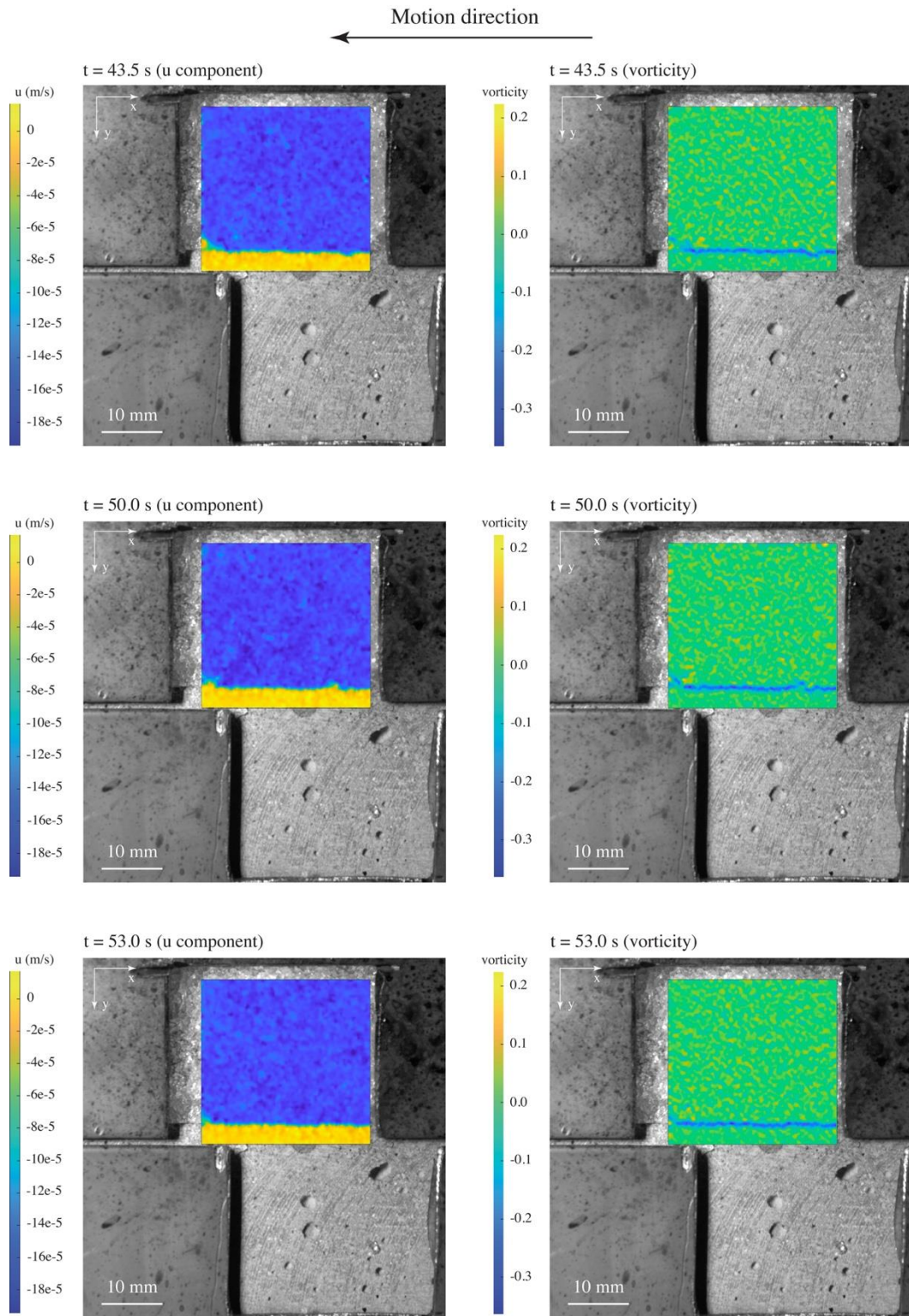
423 **Table 5** Fitting parameters obtained with Eqns. (4<sub>i</sub>) and (4<sub>ii</sub>) for all the specimens during the sliding process.  
 424 The values highlighted in italics are those selected to characterize the interface strength.

Specimens	Eqn. (4 <sub>i</sub> ) – two-parameters			Eqn. (4 <sub>ii</sub> ) – one-parameter	
	<i>a</i> (-)	<i>b</i> (kPa)	<i>R</i> <sup>2</sup> (-)	<i>a</i> (-)	<i>R</i> <sup>2</sup> (-)
LS-T1	<i>0.429</i>	<i>2.10</i>	<i>0.929</i>	0.70	0.516
LS-T2	<i>0.589</i>	<i>1.05</i>	<i>0.778</i>	0.73	0.733
SS-T1	<i>0.412</i>	<i>0.18</i>	<i>0.874</i>	0.43	0.872
SS-T2	<i>0.534</i>	<i>0.90</i>	<i>0.893</i>	0.66	0.841

### 425 3.4 Image analysis

426 As it was previously described, all tests were filmed with a digital video camera through the dedicated  
427 window on the external side of the shear box. These footages allowed to follow and compare the sensor data  
428 with the actual phenomena occurring to each sample.

429 With reference to only the sliding process the Particle Image Velocimetry (PIV, hereafter) was applied to  
430 some frames to better visualize the motion field during the test. The results do not show significant differences  
431 among the four groups of specimens. Therefore, for the sake of clarity, we depict the main results obtained by  
432 the PIV technique with reference to SS-T1 test no. 4 (Figure 7). In this case, we performed the PIV analysis  
433 on the basis of 20 frames taken at 0.5 s from each other, and between 43.5 and 53 s after the beginning of the  
434 test (i.e., 33.5 and 43 s after the failure occurrence). In Figure 7, three images are reported as example, caught  
435 at 43.5, 50, and 53 s, respectively. A rectangular ( $27.7 \times 27.1$  mm) region of interest (ROI, hereafter) was  
436 determined and the PIV analysis was carried out inside this region with the open source MATLAB app PIVlab  
437 (Thielicke and Stamhuis, 2014). It can be seen that, during the sliding process, the horizontal component of  
438 the velocity ( $\dot{u}$ ) is the same in all snow parts of the sample. The absolute value of the mean value of  $\dot{u}$  is about  
439  $1.6 \cdot 10^{-5} \text{ m s}^{-1}$ , which is substantially equivalent to the imposed displacement rate (i.e.,  $10 \text{ mm min}^{-1}$ ). Thus,  
440 one can conclude that during the test, the shear action was efficiently transmitted from the shear box to the  
441 tested specimen. The transition between these velocity values and null values (i.e., the mortar half of the  
442 specimen) happens in a very thin and horizontal band at the contact between snow and mortar, having a  
443 thickness of about 0.4 mm on average. Figure 7 also shows that in this thin layer non-null values of vorticity  
444 are present where a sort of circular movement (whirl) of snow crystals can be observed. In other zones (such  
445 as on the right part of the image at 50 s frame), this band deviates from its typical horizontal condition. This is  
446 due to some snow grains that instantaneously stop and are bypassed by others that continue their horizontal  
447 movement. A zoomed image of the contact zone is provided in Figure 8. Here, it can be observed that the  
448 instantaneous adhesion of portions of the snow layer to the underneath mortar substrate causes whirl  
449 movements (or vortices) in the neighbour snow particles (Figure 8e). A similar pattern of behaviour has been  
450 observed in other studies relating to both snow (De Biagi et al., 2019b) and granular media in general  
451 (Tordesillas et al., 2016).

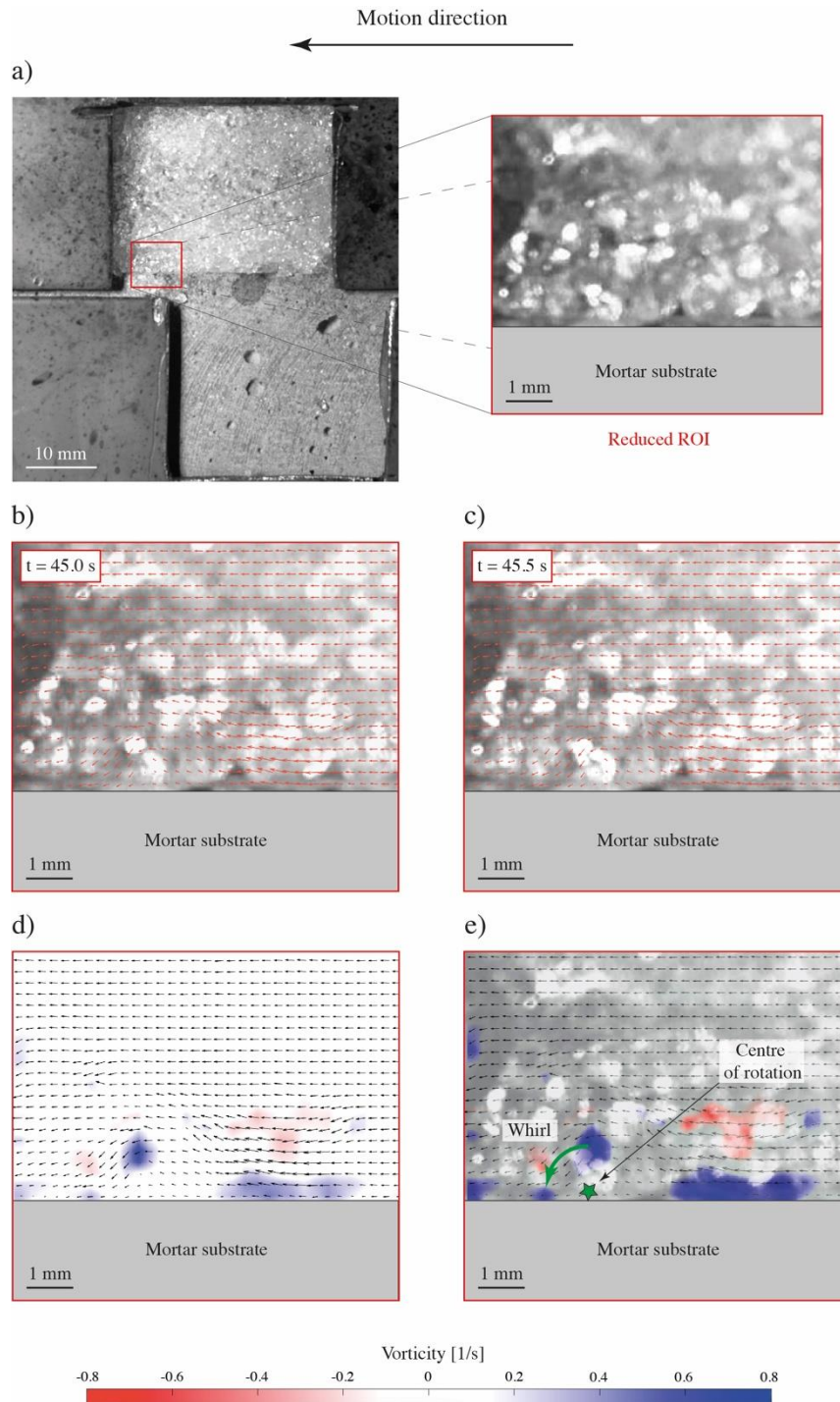


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**Figure 7** Frames of the sliding process of SS-T1 test no. 4 between 43.5 and 53 s. The horizontal component of velocity is reported on the left, while the vorticity can be seen on the right.



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456 **Figure 8** Zoomed image of the snow layer in contact with the mortar substrate (SS-T1 test no. 4): a)  
 457 Location of the reduced ROI (red rectangle) within the video frame; b) Surface pattern of snow and velocity  
 458 field (red arrows) at  $t = 45.0$  s (from the beginning of the test); c) Surface pattern of snow and velocity field  
 459 (red arrows) at  $t = 45.5$  s; d) Map of the vorticity, the red and blue areas pointed to the zones with clockwise  
 460 and counterclockwise whirls, respectively, while the white areas represent the zones with zero vorticity; e)  
 461 Map of the vorticity with snow pattern in background. The chromatic scale was emphasized to better  
 462 identify the different zones with respect to the background. The green arrow identifies a whirl movement  
 463 originated by snow particles that bypass a zone where the snow adheres to the underneath mortar substrate.  
 464 Inside this “bridge” zone the center of rotation can be clearly observed (green star).

465 **4 Discussion**

466 To evaluate the influence of the normal stress on both sintering time and temperature conditions, we assume  
 467 that the interface shear strength is governed by the Mohr-Coulomb criterion:

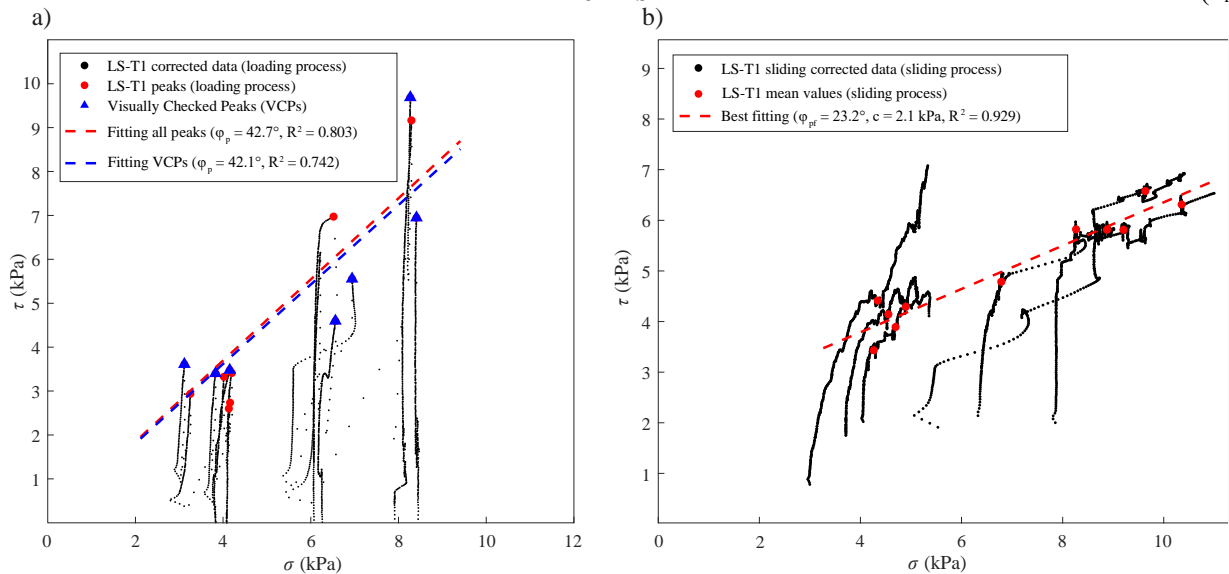
$$\tau_{l,s} = \tan \phi \sigma_{l,s} + c \quad (5)$$

468 where  $\phi$  is the equivalent friction angle of the interface,  $c$  is the parameter usually called “cohesion” in the  
 469 geotechnical literature, and subscripts  $l$  and  $s$  stand for loading and sliding processes, respectively. The same  
 470 model was applied for both processes. Within the international scientific literature, the Mohr-Coulomb law is  
 471 largely adopted in the fields of geotechnical and structural engineering for many different applications (e.g.,  
 472 soil and rock mechanics). Also, for snow mechanics the model is widely used to characterize the failure criteria  
 473 of snow samples in many experimental activities (De Biagi et al., 2019b; Matsushita et al., 2012; Podolskiy et  
 474 al., 2014). Thus, the choice of this type of model seems to be reasonable, especially in case of first experimental  
 475 results as these.

476 The estimation of the two parameters ( $\phi$  and  $c$ ) of the Mohr-Coulomb law was carried out starting from the  
 477 coefficients  $a$  and  $b$  contained in Tables 4 and 5. These coefficients are linked to  $\phi$  and  $c$  as follows:

$$\phi = \tan^{-1} a \quad (6_i)$$

$$c = b \quad (6_{ii})$$



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479 **Figure 9** a) Example of the interpretation for the loading process of LS-T1 specimens with both one-  
 480 parameter fitting laws; b) Interpretation of the sliding process for LS-T1 specimens with the two-parameters  
 481 fitting law. Red points refer to the mean values computed for the two observation windows.

482 The best estimation of the Mohr-Coulomb parameters can be found in Table 6, while an example of the  
 483 fitting results for both loading and sliding process is reported in Figure 9 for the case of LS-T1 specimens. One  
 484 can observe that a one-parameter fitting law was used for the loading process while a two-parameter expression  
 485 was adopted for the sliding one. Referring to loading process, the two possible fitting laws provide essentially  
 486 the same results, and, in most cases, the intercept calculated for the two-parameter law, i.e., the value of shear  
 487 strength for zero normal stress on the interface, was found to be very close to zero and consequently a one-  
 488 coefficient relation was adopted ( $c \approx 0$  kPa).

489 Otherwise, during the sliding process, a non-zero intercept ( $c$ ) was generally found, and a two-parameters  
 490 law was used. It can be noted that here  $c$  is devoid of a well-defined physical meaning because during sliding  
 491 process the behaviour of snow-mortar interface is strictly frictional. Therefore,  $c$  is not a cohesion parameter  
 492 and assumes only a purely mathematical significance (i.e., an intercept). The existence of  $c$  originates from the  
 493 experimental conditions adopted in this work. The entire experimental activity was indeed carried out within  
 494 a limited range of normal stresses, i.e., between 2 and 10 kPa. Thus, no further conclusions can be drawn  
 495 outside this range and the linear interpolation is only reliable inside it. For lower normal stresses, it is very  
 496 likely that the behaviour of snow-mortar interface is non-linear, and nil shear stress could be found at  $\sigma_n = 0$   
 497 kPa. In this work, the best possible (two-parameters) linearization, in the investigated pressure range, of the  
 498 supposed non-linear interface behaviour was used. On the contrary, the slope angle  $\phi$  assumes the meaning of  
 499 a friction angle for the snow-mortar interface and its tangent can be interpreted as its friction coefficient for  
 500 the sliding process.

501 **Table 6** Final values adopted for the estimation of the Mohr-Coulomb parameters for both loading and  
 502 sliding processes. The last column refers to the friction coefficients evaluated as  $\mu_{l,s} = \tan \phi_{l,s}$ .

Specimen type	Loading process			Sliding process		
	$\phi_l$ (°)	$c$ (kPa)	$\mu_l$ (-)	$\phi_s$ (°)	$c$ (kPa)	$\mu_s$ (-)
LS-T1	42.8	0.00	0.927	23.2	2.10	0.429
LS-T2	39.8	0.00	0.833	30.5	1.05	0.589
SS-T1	31.9	0.00	0.724	22.4	0.18	0.412
SS-T2	29.3	0.00	0.561	28.1	0.90	0.534

503 Despite the complex correction and interpretation procedures, the final outputs of the experimental activity  
 504 provide some interesting results. For the loading process, we conclude that the effect of sintering time on

505 friction angle is more relevant than that of temperature. In Table 6 a difference in  $\phi$  of about  $10^\circ$  can be  
506 observed passing from long sintering to short sintering times, while only  $2^\circ$  distinguishes between T1 and T2.  
507 As a general comment, we state that longer sintering times and lower temperatures induce higher friction  
508 angles. Our initial interpretation of the observed behaviour is that the larger  $\phi$ -values observed in the first  
509 phase is related to the surface adhesion acting on the snow-mortar interface (Mellor, 1975). In fact, a possible  
510 explanation is that the phenomenon occurs if water particles (or ice particles) are present on the mortar surface.  
511 Large sintering times promote the formation of “bridges” (or surface bonds) between the snow layer and the  
512 underneath rigid material, enhancing at the same time the external action needed to break them (Jelle, 2013;  
513 Jellinek, 1960). These bridges are actually adhesive bonds in which adhesive forces of electromagnetic or  
514 electrostatic nature act. The adhesive forces are responsible for the complex behaviour of snow on stiffer  
515 material that can potentially originate a high shear resistance, such as a hard snow layer firmly adhering to a  
516 pseudo-vertical surface (rock, glass, etc.). Evidence of this type of adhesion between cold snow and a solid  
517 surface can be found in some literature works (Heil et al., 2020; Inoue and Honda, 1955; Jelle, 2013; Jellinek,  
518 1960; Mellor, 1975). In the second process, on the contrary, an opposite trend emerges: it seems that the  
519 influence of temperature on shear strength is more relevant than the one of the sintering times. Smaller friction  
520 angles can be related to lower temperatures, while higher friction is promoted in warmer snowpack. With equal  
521 temperature, longer sintering time increases of only  $0.8^\circ$  and  $2.4^\circ$  the friction angle, with reference to T1 and  
522 T2, respectively.

523 Despite few works on snow-solid interface strength exist, it is possible to relate our findings with literature  
524 data. For instance, Jelle (2013) carried out a series of tilt tests with snow layers deposited on different types of  
525 substrate. He found that in case of snow-concrete the detachment of snow occurred with a tilt-angle of  $31^\circ$   
526 which corresponds to a 0.6 static friction coefficient. This value is comparable with our loading values that are  
527 ranging between 0.561 and 0.927. According to the general knowledge of materials behaviour, friction should  
528 be also dependent on the displacement rate (Persson, 2013). In particular, for snow mechanics, this dependence  
529 is extremely important and can result in the main triggering factor for avalanche release (Puzrin et al., 2019).  
530 The experimental activity described in this paper was carried out at a given displacement rate (i.e.,  $\dot{u} = 10$   
531  $\text{mm min}^{-1}$ ). Nevertheless, it is possible to relate the obtained friction coefficients to some data reported in the  
532 literature. For instance, Makkonen and Tikanmäki (2014) provided a series of friction coefficients determined

533 on the basis of tests on ice-ice, rubber-ice, steel-ice, and PMMA-ice interfaces. The tests had been conducted  
534 at a temperature of  $-10\text{ }^{\circ}\text{C}$  and different velocities were considered, ranging from  $10^{-6}$  to  $10^2\text{ m s}^{-1}$ . It was found  
535 that our results, obtained for a velocity of  $10\text{ mm min}^{-1} = 1.67 \cdot 10^{-4}\text{ m s}^{-1}$ , are consistent with the results of  
536 these literature data. For ice-ice, ice-steel and ice-PMMA interfaces, the paper gives values in the range from  
537 0.35 to 0.55, which are comparable with our sliding values that are ranging between 0.429 and 0.589.  
538 Unfortunately, the above-mentioned friction coefficients were provided only for the cited materials and only  
539 for ice which has characteristics different from seasonal snow.

## 540 **5 Conclusions**

541 In this study, we quantified the frictional behaviour of a snow layer at contact with a rigid substrate (mortar  
542 block) on the basis of a laboratory experimental campaign carried out with a portable shear test device. We  
543 performed 36 direct shear tests on artificially assembled interface specimens made by two superimposed  
544 halves: a bottom mortar block and an upper snow layer. The tests were performed at different temperatures  
545 (i.e.,  $T1 = -10\text{ }^{\circ}\text{C}$  and  $T2 = -5\text{ }^{\circ}\text{C}$ ) and sintering times (i.e., long sintering:  $LS = 20$  hours, and short sintering:  
546  $SS = 20$  minutes), to investigate the influence of these two parameters on the shear strength of the interface.

547 We also developed a methodology of analysis that provides some preliminary and promising results despite  
548 the limitations affecting the adopted testing system (i.e., variability of normal stresses, noise of the signals,  
549 etc.). In particular, the following key points arise from the present work:

- 550 • The results represent the first step in the direction of a better comprehension of many problems  
551 relating to the shear strength of a cold snow layer in contact with solids, a study still lacking of  
552 sufficient references within the international scientific literature.
- 553 • The shear strength of the tested interface can be easily interpreted by the Mohr-Coulomb criterion  
554 which allows the understanding of the two opposite behaviours in loading and sliding processes.
- 555 • The Mohr-Coulomb parameters show a clear dependence on both sintering time and temperature. In  
556 particular, two opposite trends can be observed: during the loading process, for both sintering times,  
557 the friction coefficient decreases when the room temperature increases; otherwise, in the sliding  
558 process, friction coefficient and room temperature grow together.

559 • The experimental results show the formation of a surface adhesion acting between the mortar slab  
560 and the snow layer, which is confirmed by several studies (Heil et al., 2020; Inoue and Honda, 1955;  
561 Jelle, 2013; Jellinek, 1960; Mellor, 1975). Exceeding this adhesion threshold causes the failure of  
562 the interface and the following relative sliding between the two halves of the specimen that  
563 essentially act as rigid bodies.

564 Further improvements of the shear apparatus could solve the issues affecting the present experimental  
565 activity, also confirming the interpretation of the results described here and improving them. In particular,  
566 some future modifications include:

567 • The shear device can be improved in many aspects. For instance, the variability of the normal stress  
568 can be fixed by introducing a larger air chamber directly inside the shear box which is able to  
569 maintain the pressure constant, or designing a new pneumatic system based, for example, on liquid  
570 medium instead of air.

571 • With reference to the topic of this research, one of the most interesting aspects to be studied in the  
572 future is the effect of temperatures close to the melting point of snow that could better represent the  
573 conditions of a natural ground-snow interface when the temperature is kept constant by the insulating  
574 effect of the snow cover itself. Another item, strictly related to the latter, could be the investigation  
575 of the role of liquid water content at the snow-mortar interface on both loading and sliding processes.  
576 Also, other types of snow crystals and grains, even harvested on-site, can be used to perform more  
577 reliable analyses. Finally, the only two-dimensional image analysis carried out in this work is not  
578 able to provide sufficiently reliable results that can be used to derive more general conclusion on the  
579 entire surface contact. Further improvements could overcome these limits by implementing  
580 transparent sides for the shear box or using other non-invasive techniques, such as acoustic  
581 emissions.

## 582 **Declaration of Competing Interests**

583 The authors declare that they have no known competing financial interests or personal relationships that  
584 could have appeared to influence the work reported in this paper.

585 **Author Contribution**

586 Gianmarco Vallero: Conceptualization, methodology, formal analysis, writing – original data, writing –  
587 review & editing, visualization. Monica Barbero: investigation, data curation, writing – review & editing,  
588 supervision. Fabrizio Barpi: investigation, data curation, writing – review & editing, supervision. Mauro Borri-  
589 Brunetto: investigation, data curation, writing – review & editing, supervision. Valerio De Biagi: writing –  
590 review & editing, supervision. Yoichi Ito: investigation, data curation, writing – review & editing. Satoru  
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600 **Appendices**

601 *Appendix A*

602 **Table A.1** Corrected data for both loading and sliding processes and for all the tested specimens.  $\sigma_{VCP}$  and  
 603  $\tau_{VCP}$  represent the stress components for all the VCPs.  $\bar{\sigma}_1$  and  $\bar{\tau}_1$  are the mean value within the first window  
 604 of the sliding process, while  $\bar{\sigma}_2$  and  $\bar{\tau}_2$  are referred to the second window. Notes: 1) missing data; 2) test not  
 605 considered for both loading and sliding analyses because of the global collapse of the specimen that  
 606 compromise the test output; 3) test not considered because the motor does not reach the required  
 607 displacement rate; 4) test in which only the loading process was considered because during the sliding  
 608 process the relative movement between the two halves of the specimen was compromised by the collapse  
 609 of the sample; 5) test in which only the sliding process was considered because during the loading process  
 610 the detachment of the snow layer is not clear in the video recording of the test.

Test extended name	Loading process			Sliding process				Notes
	$u$ at failure (mm)	$\sigma_{VCP}$ (kPa)	$\tau_{VCP}$ (kPa)	$\bar{\sigma}_1$ (kPa)	$\bar{\tau}_1$ (kPa)	$\bar{\sigma}_2$ (kPa)	$\bar{\tau}_2$ (kPa)	
LS-T1 test no. 1	3.38	3.12	3.61	4.34	4.41	5.11	5.95	
LS-T1 test no. 2	3.02	4.15	3.48	4.26	3.43	4.69	3.89	
LS-T1 test no. 3	2.00	3.83	3.40	4.55	4.14	4.90	4.29	
LS-T1 test no. 4	-	-	-	-	-	-	-	3)
LS-T1 test no. 5	4.15	6.56	4.60	6.79	4.78	8.27	5.82	
LS-T1 test no. 6	-	-	-	-	-	-	-	2)
LS-T1 test no. 7	2.50	8.27	9.69	8.88	5.81	9.64	6.58	
LS-T1 test no. 8	3.61	8.41	6.95	9.20	5.81	10.35	6.31	
LS-T1 test no. 9	-	-	-	-	-	-	-	
LS-T2 test no. 1	1.16	4.14	4.19	5.29	4.74	6.09	5.17	
LS-T2 test no. 2	-	-	-	-	-	-	-	1)
LS-T2 test no. 3	1.72	5.10	4.46	5.50	3.82	5.73	3.87	
LS-T2 test no. 4	1.04	5.98	3.46	7.01	5.36	7.52	5.50	
LS-T2 test no. 5	0.70	5.94	3.92	7.66	6.28	8.60	6.46	
LS-T2 test no. 6	4.87	6.15	6.45	6.66	4.45	7.80	5.07	
LS-T2 test no. 7	-	-	-	-	-	-	-	3)
LS-T2 test no. 8	1.76	8.55	7.50	9.27	6.21	10.07	6.96	
LS-T2 test no. 9	-	-	-	-	-	-	-	2)
SS-T1 test no. 1	-	-	-	-	-	-	-	1)
SS-T1 test no. 2	-	-	-	-	-	-	-	2)
SS-T1 test no. 3	3.30	4.26	4.26	-	-	-	-	4)
SS-T1 test no. 4	0.77	5.96	4.35	6.63	2.85	7.46	3.03	
SS-T1 test no. 5	0.50	6.12	4.78	6.49	2.75	7.46	3.64	
SS-T1 test no. 6	4.38	6.68	3.85	7.19	4.78	7.58	5.88	
SS-T1 test no. 7	-	-	-	8.96	3.97	10.02	4.51	5)
SS-T1 test no. 8	-	-	-	-	-	-	-	2)
SS-T1 test no. 9	-	-	-	9.04	3.91	10.06	4.02	5)
SS-T2 test no. 1	2.84	4.56	3.14	4.79	3.46	5.47	4.03	
SS-T2 test no. 2	3.49	4.48	2.78	5.71	4.21	6.11	4.63	
SS-T2 test no. 3	6.47	4.13	1.69	5.33	3.52	5.63	3.90	
SS-T2 test no. 4	4.71	6.70	3.88	6.86	4.39	8.08	4.85	
SS-T2 test no. 5	3.58	7.00	3.58	7.17	4.45	7.76	4.71	
SS-T2 test no. 6	-	-	-	-	-	-	-	2)
SS-T2 test no. 7	-	-	-	8.75	5.58	9.94	6.67	5)
SS-T2 test no. 8	-	-	-	-	-	-	-	2)
SS-T2 test no. 9	-	-	-	-	-	-	-	2)

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612 **References**

- 613 Abele, G., 1963. A correlation of unconfined compressive strength and ram hardness of processed snow.  
614 CRREL Tech. Rep. 14.
- 615 Ancy, C., Bain, V., 2015. Dynamics of glide avalanches and snow gliding. *Rev. Geophys.* 53, 745–784.  
616 <https://doi.org/10.1002/2015RG000491>
- 617 Barbero, M., Barpi, F., Borri-Brunetto, M., Pallara, O., 2016. An apparatus for in situ direct shear tests on  
618 snow. *Exp. Tech.* 40, 149–158.
- 619 Bartko, M., Baskaran, A., 2018. Snow Friction Coefficient for Commercial Roofing Materials. *J. Cold Reg.*  
620 *Eng.* 32, 06017005. [https://doi.org/10.1061/\(asce\)cr.1943-5495.0000146](https://doi.org/10.1061/(asce)cr.1943-5495.0000146)
- 621 Casassa, G., Narita, H., Maeno, N., 1991. Shear cell experiments of snow and ice friction. *J. Appl. Phys.* 69,  
622 3745–3756. <https://doi.org/10.1063/1.348469>
- 623 Casassa, G., Narita, H., Maeno, N., 1989. Measurements of friction coefficients of snow blocks. *Ann.*  
624 *Glaciol.* 13, 40–44. <https://doi.org/10.1017/s0260305500007618>
- 625 Colbeck, S.C., 1994. A review of the friction of snow skis. *J. Sports Sci.* 12, 285–295.
- 626 Conway, H., Abrahamson, J., 1984. Snow stability index. *J. Glaciol.* 30, 321–327.
- 627 De Biagi, V., Barbero, M., Barpi, F., Borri-Brunetto, M., Pallara, O., 2019a. Improvements on an existing  
628 testing device to study post-peak shear behaviour of snow. *Geophys. Res. Abstr.* 21.
- 629 De Biagi, V., Barbero, M., Barpi, F., Borri-Brunetto, M., Podolskiy, E., 2019b. Failure mechanics of snow  
630 layers through image analysis. *Eur. J. Mech. A/Solids* 74, 26–33.  
631 <https://doi.org/10.1016/j.euromechsol.2018.10.018>
- 632 Fierz, C., Armstrong, R.L., Durand, Y., Etchevers, P., Greene, E., McClung, D.M., Nishimura, K.,  
633 Satyawali, P.K., Sokratov, S.A., 2009. The international classification for seasonal snow on the  
634 ground.
- 635 Gauthier, D., Brown, C., Jamieson, B., 2010. Modeling strength and stability in storm snow for slab

- 636 avalanche forecasting. *Cold Reg. Sci. Technol.* 62, 107–118.  
637 <https://doi.org/10.1016/j.coldregions.2010.04.004>
- 638 Gleason, J., 2002. Preliminary results of snow surface friction coefficient measurements, in: *International*  
639 *Snow Science Workshop*. pp. 523–527.
- 640 Heil, J., Mohammadian, B., Sarayloo, M., Bruns, K., Sojoudi, H., 2020. Relationships between surface  
641 properties and snow adhesion and its shedding mechanisms. *Appl. Sci.* 10.  
642 <https://doi.org/10.3390/APP10165407>
- 643 Höller, P., Fromm, R., 2010. Quantification of the hand hardness test. *Ann. Glaciol.* 51, 39–44.  
644 <https://doi.org/10.3189/172756410791386454>
- 645 Inoue, R., Honda, T., 1955. Measurement of Adhesion between Snow and a Solid Surface. *J. Japanese Soc.*  
646 *Snow Ice* 17, 18–20.
- 647 Jelle, B.P., 2013. The challenge of removing snow downfall on photovoltaic solar cell roofs in order to  
648 maximize solar energy efficiency - Research opportunities for the future. *Energy Build.* 67, 334–351.  
649 <https://doi.org/10.1016/j.enbuild.2013.08.010>
- 650 Jellinek, H.H.G., 1960. *Adhesive Properties of Ice, Part II*. Wilmette, Illinois.
- 651 Kietzig, A.M., Hatzikiriakos, S.G., Englezos, P., 2010. Physics of ice friction. *J. Appl. Phys.* 107.  
652 <https://doi.org/10.1063/1.3340792>
- 653 Kietzig, A.M., Hatzikiriakos, S.G., Englezos, P., 2009. Ice friction: The effects of surface roughness,  
654 structure, and hydrophobicity. *J. Appl. Phys.* 106. <https://doi.org/10.1063/1.3173346>
- 655 Makkonen, L., Tikanmäki, M., 2014. Modeling the friction of ice. *Cold Reg. Sci. Technol.* 102, 84–93.  
656 <https://doi.org/10.1016/j.coldregions.2014.03.002>
- 657 Matsushita, H., Matsuzawa, M., Abe, O., 2012. The influences of temperature and normal load on the shear  
658 strength of snow consisting of precipitation particles. *Ann. Glaciol.* 53, 31–38.  
659 <https://doi.org/10.3189/2012AoG61A022>
- 660 McCallum, A., 2014. Cone Penetration Testing (CPT): A valuable tool for investigating polar snow. *J.*

661 Hydrol. New Zeal. 52, 97–113.

662 McCallum, A., White, G.W., 2016. Engineered Pavement of Snow and Ice, in: 8th International Conference  
663 on Snow Engineering. Centre Scientifique et Technique du Bâtiment (CSTB), Nantes (France).

664 McCallum, A., Wiegand, A., 2018. Simple Method for Estimating Snow Strength Using CPT Sleeve Friction  
665 Data. *J. Cold Reg. Eng.* 32, 04018013. [https://doi.org/10.1061/\(asce\)cr.1943-5495.0000170](https://doi.org/10.1061/(asce)cr.1943-5495.0000170)

666 McClung, D., Schaerer, P.A., 2006. *The avalanche handbook*. Mountaineers Books.  
667 <https://doi.org/10.5860/choice.31-3797>

668 McClung, D.M., 1979. Shear fracture precipitated by strain softening as a mechanism of dry slab avalanche  
669 release. *J. Geophys. Res. Solid Earth* 84, 3519–3526. <https://doi.org/10.1029/JB084iB07p03519>

670 McClung, D.M., 1977. Direct Simple Shear Tests on Snow and Their Relation to slab avalanche formation.  
671 *J. Glaciol.* 19, 101–109.

672 Mede, T., Chambon, G., Hagenmuller, P., Nicot, F., 2018. Snow Failure Modes Under Mixed Loading.  
673 *Geophys. Res. Lett.* 45, 13,351-13,358. <https://doi.org/10.1029/2018GL080637>

674 Mellor, M., 1975. A review of basic snow mechanics. *Snow Mech.* (Proceedings Grindelwald Symp. April  
675 1974), IAHS Publ. no. 114 251–291.

676 Mitterer, C., Schweizer, J., 2012. Towards a better understanding of glide-snow avalanche formation. *Int.*  
677 *Snow Sci. Work.* 610–616.

678 Persson, B., 2013. *Sliding friction: physical principles and applications*. Springer-Verlag Berlin Heidelberg.  
679 <https://doi.org/10.1007/978-3-662-04283-0>

680 Podolskiy, E.A., Barbero, M., Barpi, F., Chambon, G., Borri-Brunetto, M., Pallara, O., Frigo, B., Chiaia, B.,  
681 Naaim, M., 2014. Healing of snow surface-to-surface contacts by isothermal sintering. *Cryosphere* 8,  
682 1651–1659. <https://doi.org/10.5194/tc-8-1651-2014>

683 Portnoff, M.R., 1980. Time-Frequency Representation of Digital Signals and Systems Based on Short-Time  
684 Fourier Analysis. *IEEE Trans. Acoust. Speech, Signal Process.* 28, 55–69.

685 Puzrin, A.M., Faug, T., Einav, I., 2019. The mechanism of delayed release in earthquake-induced  
686 avalanches. *Proc. R. Soc. A Math. Phys. Eng. Sci.* 475. <https://doi.org/10.1098/rspa.2019.0092>

687 Reiweger, I., Ernst, R., Schweizer, J., Dual, J., 2009. Force-controlled shear experiments with snow samples.  
688 *ISSW 09 - Int. Snow Sci. Work. Proc.* 120–123.

689 Reiweger, I., Schweizer, J., Ernst, R., Dual, J., 2010. Load-controlled test apparatus for snow. *Cold Reg. Sci.*  
690 *Technol.* 62, 119–125. <https://doi.org/10.1016/j.coldregions.2010.04.002>

691 Schweizer, J., Jamieson, J.B., Schneebeli, M., 2003. Snow avalanche formation. *Rev. Geophys.* 41.  
692 <https://doi.org/10.1029/2002RG000123>

693 Shapiro, L., Johnson, J., Sturm, M., Blaisdell, G., 1997. *Snow Mechanics - Review of the State of*  
694 *Knowledge and Applications.*

695 Sugiura, K., Yang, D., Ohata, T., 2011. Rapid change of tundra snow hardness in Alaska. *Ann. Glaciol.* 52,  
696 97–101. <https://doi.org/10.3189/172756411797252040>

697 Takeuchi, Y., Nohguchi, Y., Kawashima, K., Izumi, K., 1998. Measurement of snow-hardness distribution.  
698 *Ann. Glaciol.* 26, 27–30.

699 Thielicke, W., Stamhuis, E.J., 2014. PIVlab – Towards User-friendly, Affordable and Accurate Digital  
700 Particle Image Velocimetry in MATLAB. *J. Open Res. Softw.* 2. <https://doi.org/10.5334/jors.bl>

701 Tordesillas, A., Pucilowski, S., Lin, Q., Peters, J.F., Behringer, R.P., 2016. Granular vortices: Identification,  
702 characterization and conditions for the localization of deformation. *J. Mech. Phys. Solids* 90, 215–241.  
703 <https://doi.org/10.1016/j.jmps.2016.02.032>

704 Turner, D., Crozier, P., Reu, P., 2015. *Digital Image Correlation Engine.*

705 White, G., McCallum, A., 2018. Review of ice and snow runway pavements. *Int. J. Pavement Res. Technol.*  
706 11, 311–320. <https://doi.org/10.1016/j.ijprt.2017.11.002>

707