buildings

MDPI

Article

Experimental Study on Shear Strength of Roof–Snow Interfaces for Prediction of Roof Snow Sliding

Xinli Cao [1,2], Huamei Mo [1,2,*], Guolong Zhang [1,2], Qingwen Zhang [1,2] and Feng Fan [1,2]

1 Key Lab of Structures Dynamic Behavior and Control of the Ministry of Education, Harbin Institute of Technology, Harbin 150090, China
2 Key Lab of Smart Prevention and Mitigation of Civil Engineering Disasters of the Ministry of Industry and Information Technology, Harbin Institute of Technology, Harbin 150090, China
* Correspondence: mohuamei@hit.edu.cn

Abstract: The sliding of roof snow may result in surcharges of snow load on lower roofs or the injury of pedestrians on the ground. It is therefore of great significance to study the mechanism of roof snow sliding, such that prevention or control measures can be developed to manage the risk. Considering four commonly used roofing materials, glass, steel, membrane, and concrete, two types of experiments were carried out in this study to possibly reveal the influence of roofing materials on the shear strength of the roof–snow interface: one is the critical angle tests where the angle at which the snow starts to slide off from the roof is tested, and the other is the shearing tests which aim to test the shear strength of the roof–snow interfaces at specific temperatures. The results showed that the critical angle for roof snow sliding, as well as the shear strength of the roof–snow interface for the four considered roofing materials, show a U-shape trend with the increase in surface roughness and that the shear strength of the roof–snow surface ranges from 0.15 kPa to 2 kPa for the cases considered, while the strength reaches its maximum at certain temperatures near −5 °C for a specific roofing material and snow thickness. These findings could be a useful reference for future experimental or simulation studies on roof snow sliding.

Keywords: roof snow sliding; roofing materials; critical angle; shear strength; roof–snow interface

Citation: Cao, X.; Mo, H.; Zhang, G.; Zhang, Q.; Fan, F. Experimental Study on Shear Strength of Roof–Snow Interfaces for Prediction of Roof Snow Sliding. *Buildings* **2024**, *14*, 1036. https://doi.org/10.3390/buildings14041036

Academic Editor: Duc-Kien Thai

Received: 9 February 2024
Revised: 9 March 2024
Accepted: 4 April 2024
Published: 8 April 2024

1. Introduction

The sliding of roof snow has frequently been observed in snowy regions, which may result in surcharges of snow load on lower roofs or the injury of pedestrians on the ground. Consequently, it is significant to study the mechanism of roof snow sliding, such that prevention or control measures can be developed to manage the risk. From this perspective, it is essential to investigate the shear strength of the roof–snow interface.

Influenced by factors such as temperature, humidity, and building heating, the physical properties of the roof–snow interface start to evolve from the moment when snow accumulates on the roof [1–3]. Snow particles on the interface begin to melt and transform after receiving energy from the environment, and this process is called "sintering", a term referenced from the field of metallurgy. Study [4] indicated that snow sintering not only occurs above 0 °C but also at temperatures as low as −15 °C, while the degree of sintering increases when the temperature rises. Initially, the type of contact between snow particles and that between the snow and the roof is point contact. With the occurrence of the sintering, the point contact is converted to face contact. As the sintering intensifies, the bonding force between snow particles (cohesion) and that between the snow and roof (adhesion) increases. It was indicated by De Biagi et al. [5] that the snow specimen is able to carry a shear load even at low normal stress with almost instantaneous sintering. However, if the temperature continues to rise, the snow particles will start to melt, which will reduce the bonding force on the roof–snow interface. Finally, the downhill force caused by the gravity of snow on the sloped roof surpasses the bonding force and friction force between the roof and the snow layer, causing the sliding of the roof snow. In fact, it was indicated by Tayler [6] that snow slides from the roof when the 0 °C isotherm reaches the roof–snow interface, which causes the snow to melt and further lubricates the roof surface, destroying the bonding and friction forces between the roof and snow.

The sliding of roof snow is a very complex process that is affected by many factors. Factors such as roof materials, snow thickness, air temperature, indoor heating, and the deposit history of snow particles could all affect the occurrence or behavior of roof snow sliding. For example, it was pointed out by Williams et al. [7] that factors such as roofing materials and roof surface temperature have a significant impact on ice/snow sliding. The increase in atmospheric temperature promotes the melting of ice/snow on roofs, reducing the bonding and friction forces between ice/snow and roof materials and leading to the sliding of roof ice/snow. Similarly, it was stated by Mellor [8] that the bond strength of the snow–solid surface usually increases with decreasing temperature and varies with the surface properties of the solid material, such as roughness and hydrophobicity. Takakura et al. [9] further indicated that snow sliding is not only influenced by the roof slope but also by the atmospheric temperature in different regions, with a positive correlation between ambient temperature and the occurrence probability of roof snow sliding. This was also verified by Vallero et al. [10], who pointed out that during the loading process, the friction coefficient of the snow-mortar interface decreases when the room temperature increases. By using field test data of snow sliding on metal roofs that are associated with different slopes and taking into account the effects of snow characteristics and atmospheric temperature, Sack et al. [2] established a statistical model to describe the occurrence of snow sliding on roofs and pointed out that the essential forces resisting snow sliding from unobstructed shed roofs are the bonding force and friction force. Jelle [11] found that snow/ice can adhere vertically to glass surfaces under certain specific climatic conditions, indicating the significant influence of bonding force on roof snow sliding. More specifically, it was Heil et al.'s [12] opinion that the snow adheres to a solid surface strongly when the liquid water content is around 20%. By considering certain typical commercial roofing materials such as membranes made of polyvinyl chloride and modified bitumen and painted industrial metal sheets, Bartko and Baskaran [13] found that the average sliding angle of snow on these surfaces ranges from 6° to 57°. Jamieson and Johnston [3] used a shear frame to measure the shear strength of thin, weak snowpack layers that is critical for slab avalanche release and found that the shear strength of the weak layers ranges from 0.1 to 2 kPa, indicating the large variability of shear strength of snow layers. Some scholars have studied the shear strength of ice–ice interfaces and indicated that the strength is 550 ± 120 kPa [14–16], which is much higher than the shear strength of snow layers.

The complexity of the roof–snow interface makes it difficult to predict the sliding of roof snow. As a compromise, some simple assumptions need to be made when studying the sliding of roof snow. For example, in a study that focused on the frequency of roof snow sliding on sloped roofs, Isyumov and Mikitiuk [17] took the atmospheric temperature of 0 °C as the condition for roof snow sliding. The same criterion for temperature was adopted by Zhou et al. [18,19] while another condition was applied: the amount of liquid water included in the snow layer exceeds the maximum water-holding capacity of the snow layer (taken as 3% of the snow layer's volume). Both assumptions were too simple and could not reflect the actual condition of the roof–snow interface. This illustrates the challenge of the study on roof snow sliding.

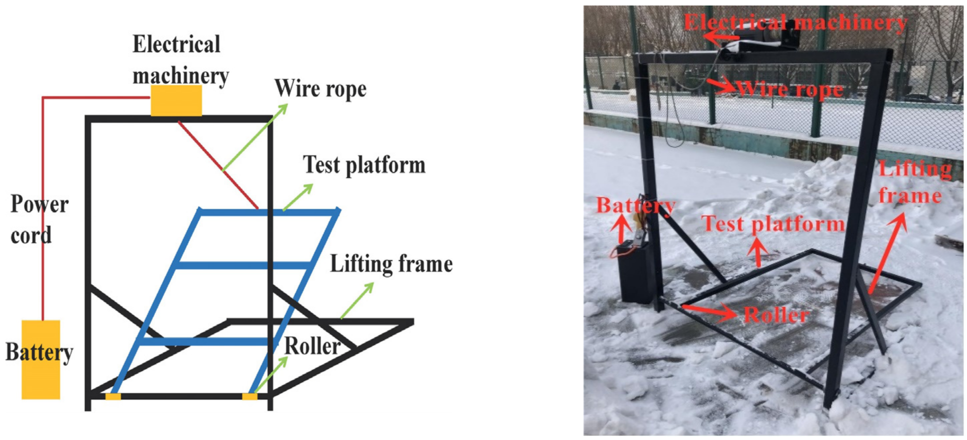
To possibly reveal the influence of roofing materials on the shear strength of the roof–snow interface, which is essential for deciding the criterion for the occurrence of snow sliding on building roofs, this paper investigates the shear strength of the roof–snow interface by considering four commonly used roofing materials: glass, steel, membrane, and concrete. Two types of experiments are conducted: one is designed to test the critical angle at which the snow starts to slide off from the roof, and the other is the shearing test, which is aimed to test the shear strength of the roof–snow interfaces at specific temperatures. It should be noted that the results presented in this study should be regarded as comparative since the snow and test conditions may vary on other occasions. The remaining part of the paper is organized as follows: the details and results of the critical angle tests and the shearing tests are presented in Sections 2 and 3, respectively, and the conclusions are given in Section 4 based on the findings of the experiments.

2. Critical Angle Tests

The direct influence of roofing materials on the roof snow sliding is that the critical angle at which the snow starts to slide off from the roof is different. This is because different roofing materials are associated with different roughness lengths. The actual contact area between the snow particles and the roof surface is then different among different materials, which will further result in different adhesion and friction coefficients on the roof–snow interface. It is therefore interesting and essential to quantify such differences.

2.1. Test Setup

The tests are carried out by slightly changing the slope of the roof model until the snow block slides off. For this purpose, by referring to the 2013 ASTM (American Society for Testing and Materials) standard guide for measuring the coefficient of friction [20], an apparatus capable of lifting the roof model is designed and fabricated, which is shown in Figure 1. The main structure of the apparatus includes a steel frame that supports all related devices and a test platform that is used to place the roof model. The size of the steel frame is 1.1 m in width and 1.5 m in height, and the platform has a width of 0.8 m and a length of 1.2 m. The test platform and the steel frame are connected by roller axles, allowing for the free rotation of the test platform along the rounded corners, and the rotation of the test platform is made by a wire rope that is fixed at the end of the platform and connected to the electric winch that is installed at the top of the steel frame. The motor of the electric winch is 1.1 kW or 1.4 hp in power, and the transmission mode is planetary gear transmission, providing a rated pulling force of about 1350 kg and a gear ratio of 150:1. The winch is powered by a 12 V, 18 Ah lithium battery which could work at temperatures as low as −20 °C. To reduce the vibration caused by lifting the test platform, a speed control switch is installed to ensure the test platform is lifted evenly and slowly.



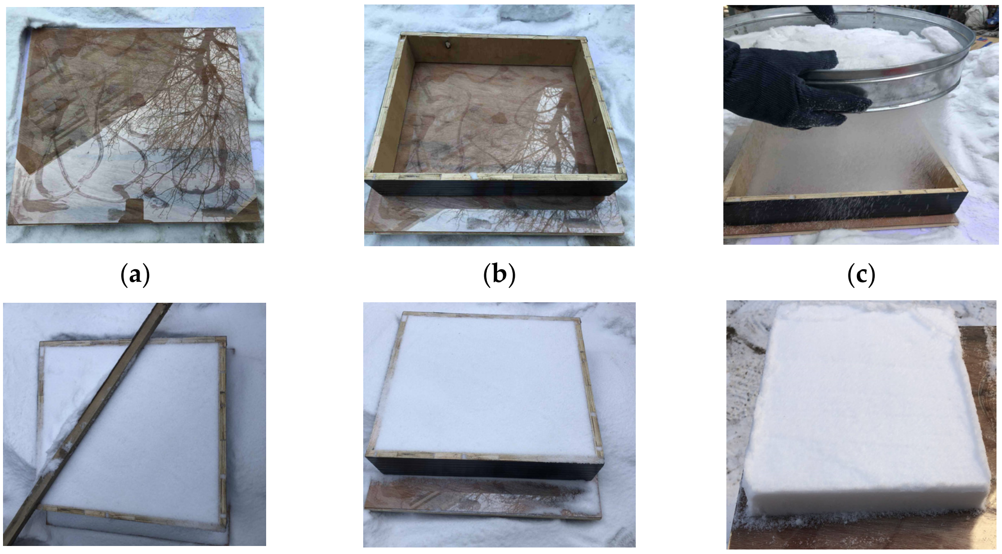
(**a**) (**b**)

Figure 1. Diagram and photo of the roof lifting apparatus used in the critical sliding angle tests: (**a**) the diagram; (**b**) the photo.

2.2. Specimen Preparation

In the current study, four types of roofing materials are considered, i.e., concrete, membrane, steel, and glass. The roughness lengths of the materials are 5.535 µm, 3.913 µm, 3.179 µm, and 0.051 µm, respectively, for these four types of roofing materials [16]. Concrete is the roughest, while glass is the smoothest among the four materials. The membrane and the steel are moderate and close to each other. To carry out the critical angle tests for roof snow sliding, specimens with dimensions of 0.5 m × 0.5 m of the roofing materials are prepared. Considering that the stiffnesses of the specimens are quite low, they are pasted to a plywood board that is 8 mm in thickness by glass adhesive.

Before snow blocks are presented on the roof model, a wooden frame of 0.3 m × 0.3 m in size is placed on the roof model, and the height of the wooden frame is dependent on the depth of the snow block. Natural snow is then sifted down onto the roof model until the area of the wooden frame is fully filled with snow; the top of the snow block is then leveled using a ruler. The depth of the snow block is attained by changing the height of the wooden frame. When the snow block is accomplished, the time of the accomplishment is recorded to make sure that the time duration between the accomplishment of the making and testing of the snow blocks is the same. The steps for preparing the test specimens are illustrated in Figure 2.



(**a**) (**b**) (**c**)
(**d**) (**e**) (**f**)

Figure 2. Steps for making the snow block used in the tests: (**a**) make the roof panel; (**b**) place the wooden frame; (**c**) sift the snow; (**d**) level the top of the snow block (**e**) remove the wooden frame; (**f**) obtain the snow block for tests.

2.3. Test Process

The tests are carried out in an outdoor area that is closely surrounded by buildings so that no direct sunlight can be received by the specimen, and the wind is greatly weakened. This is to minimize the impact of solar radiation on the morphological change in the snow particles and the impact of the wind on the sliding of the snow block. In addition, the temperature during the tests was consistently below −10 °C, and no snow melting occurred. The test conditions for each test are kept consistent to ensure a reliable comparison of the test results.

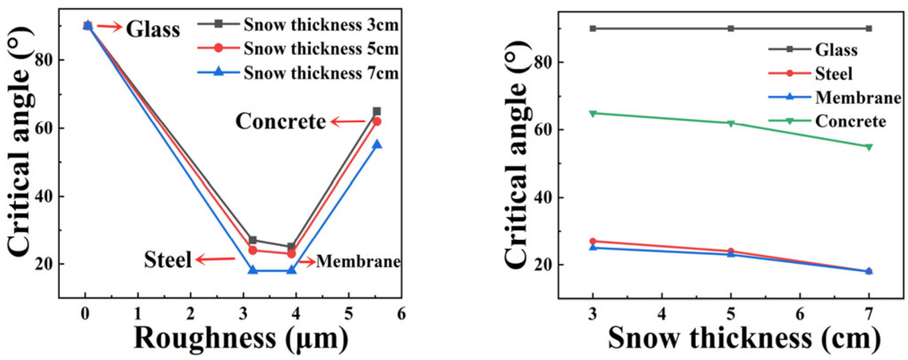
At the start of each test, the test platform of the lifting apparatus is firstly adjusted to be horizontal; the roof model that is covered with snow block is thereafter placed carefully on the test platform, making sure that the roof–snow interface is above the upper edge of the frame of the test platform while the roof panel can be seized by the frame. The electric winch is switched on to lift the far end of the test platform after the specimen is in position, and the lifting speed is controlled to be less than 0.01 m/s, so the slope of the platform and the roof panel are changed evenly and slightly. The lifting is switched off when the snow block starts to slide off from the roof panel, and the angle of the roof panel is measured and recorded as the test result. An illustration of the test process is shown in Figure 3.

(**a**) (**b**) (**c**) (**d**)

Figure 3. Test process of the critical angle tests for roof snow sliding: (**a**) place the specimen on the test platform; (**b**) rotate the roof model slowly; (**c**) stop rotating when the snow slides; (**d**) measure the roof angle.

2.4. Test Results

For each type of roofing material, snow thicknesses of 3 cm, 5 cm, and 7 cm are considered, so there are 12 tests in total in the experiment. The test results are shown in Figure 4, where Figure 4a depicts the variation in the critical angle with the roofing materials, and Figure 4b shows the change in the critical angle with snow thickness. It can be seen from Figure 4a that the critical angle does not monotonically increase or decrease with the increase in roughness of roofing materials but exhibits a U-shape distribution, i.e., the smoothest glass is associated with the largest critical angle, and the roughest concrete takes the second place. The angles for the steel and membrane, which are moderate in roughness, are relatively small and close to each other. This is interesting and inconsistent with our prediction that the angle should increase monotonically with the increase in roughness. This is mainly caused by the fact that the bonding force is positively related to the actual contact area between the snow particles and the roof surface, and the smoother the surface is, the larger the contact area is, resulting in a higher bonding force. In other words, the bonding force is negatively related to the roughness of the surface. In contrast, the friction force is positively related to the roughness; the opposite trend of the two forces with the roughness results in the U shape observed in Figure 4a. However, the contribution of bonding force and friction force in the determination of critical angle is unclear and deserves further investigation. This is unfortunately outside of the scope of this study and could not be discussed.



(**a**) (**b**)

Figure 4. Variation in the critical sliding angle with roofing materials and with snow thickness: (**a**) variation in roofing materials; (**b**) variation in snow thickness.

The results shown in Figure 4b indicate that the critical angle decreases with the increase in snow thickness except in the case of glass. This is understandable because for the same roofing material, the shear strength of the roof–snow interface is almost the same for different snow thicknesses, but the higher snow thickness will result in greater gravity, which will further accelerate the sliding of the snow. The critical angle for the glass remains 90° for all considered snow thicknesses. This indicates that the shear strength of the roof–snow interface for glass is dominated by the bonding force. This is consistent with the observation made by Jelle [11] who found that snow/ice can adhere vertically to glass surfaces under certain climatic conditions.

3. Shearing Tests

The critical angle tests presented in Section 2 qualitatively revealed the impact of the roofing materials on the roof snow sliding. However, a more specific parameter, the shear strength of the roof–snow interface, is desired for the prediction of roof snow sliding. For this purpose, an experiment is carried out to test the shear strength of the roof–snow interface in this section; details of the tests are given below.

3.1. Test Design

The experiment is conducted in the Low-Temperature Laboratory of the School of Civil Engineering at Harbin Institute of Technology. The lab utilizes the low temperature in the winter in Harbin, and the indoor temperature is controlled by a heating system installed on the walls of the lab. Therefore, the indoor temperature of the lab could not be set to be lower than the outdoor temperature. Considering that the outdoor temperature in the winter of Harbin could often be lower than −10 °C even in the daytime, the lab could provide a suitable environment for the tests.

The internal size of the lab is 3 m × 3 m, and the structure of the wall is arranged as follows (from the outside to the inside): enclosure structure → reflective film → electric heating film → wooden board (Figure 5). The enclosure structure is made of polyethylene insulation material, while the reflective film is made of aluminum foil and polyethylene bubble film, which is 6 mm thick. The electric heating film is made of graphene electric heating material, with a power of 220 W/m^2, and the surface temperature can reach up to 40 °C. The thickness of the wooden board is 8 mm, which allows for the heat generated by the electric heating film to be evenly transmitted indoors. In addition, a temperature control module is installed to control the temperature, which consists of a temperature controller, an AC contactor, and a temperature sensor; the error of the temperature control module is within ±0.5%.

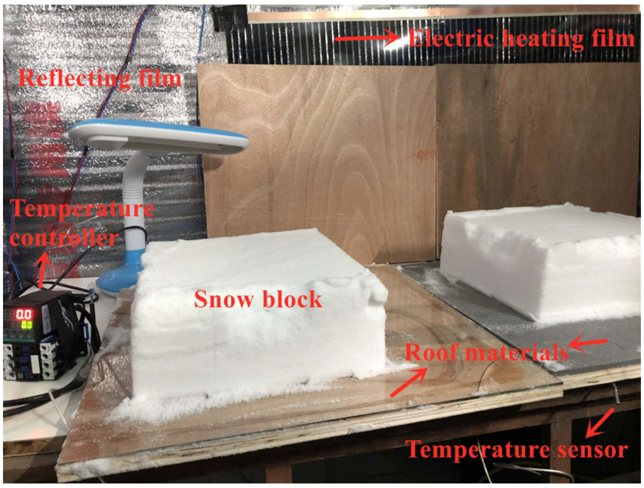
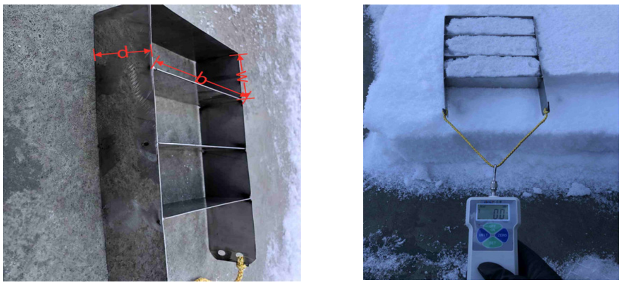


Figure 5. Graphical illustration of the low-temperature laboratory.

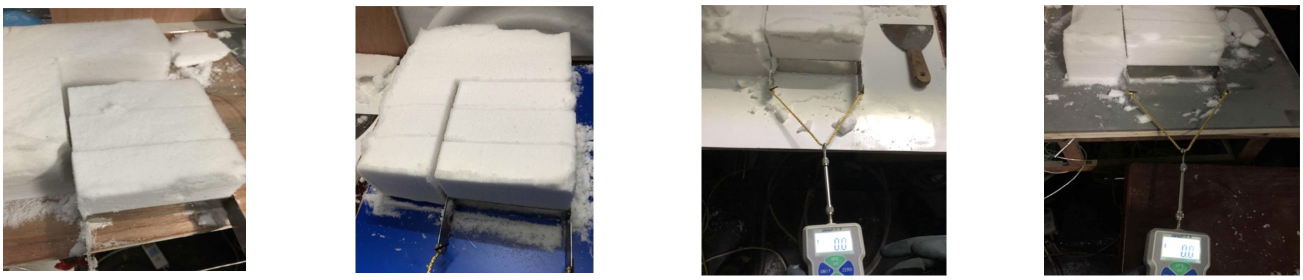
Specimens are prepared by following the procedures given in Section 2.2, and the shearing of the roof–snow interfaces will be conducted by the shearing frame shown in Figure 6a. The shearing frame is made by following references [3], which is made of 0.6 mm thick stainless steel, and the size for each sub-grid is w = 53 mm, b = 153 mm, and d = 40 mm.



(**a**) (**b**)

Figure 6. The shearing frame used in the shearing tests: (**a**) photo of the shearing frame; (**b**) application of the shearing frame.

The shearing frame is connected with a tension meter before it is embedded into the bottom of the snow block. The tension meter is a digital push–pull force gauge of HP-500 type with a maximum load of 500 N and a resolution of 0.1 N. When pulling the shearing frame, the tension force will be indicated by the tension meter (Figure 6b), and the force when the sampled snow starts to slip on the roof panel is recorded as the ultimate shear force. The shear strength of the roof–snow interface is then derived by dividing the ultimate shear force with the area of the shearing frame. Example photos of the shearing tests can be found in Figure 7. It is worth noting that during the test, the angle and speed of pulling will have an impact on the measurement results. Therefore, the shearing frame should be pulled horizontally at a uniform speed to ensure the accuracy of the measurement.



(**a**) (**b**) (**c**) (**d**)

Figure 7. Shearing of roof–snow interfaces for different roofing materials: (**a**) glass–snow; (**b**) steel–snow; (**c**) membrane–snow; (**d**) concrete–snow.

3.2. Results and Discussion

By considering the four roofing materials mentioned earlier, temperatures of −15 °C, −10 °C, −5 °C, and 0 °C, and snow thicknesses of 5 cm, 10 cm, and 15 cm, a total number of 48 tests are carried out in the experiment.

The results show that the shear strength of the roof–snow interface ranges from 0.15 kPa to 2 kPa for the considered cases in this study. This is consistent with that found by Jamieson and Johnston [3], which focused on the shear strength of snow layers. Figure 8 shows the variation in the shear strength of the roof–snow interface with the change in roof materials. It can be seen from the figure that a trend of a "U" shape similar to Figure 4a is observed. This further verifies the explanation given in Section 2.4. In addition, it is interesting to find that the "U" shape is gradually flattened when the temperature changes from −5 °C to −10 °C and further to −15 °C. By considering that the friction force is only related to the roughness (when the normal stress remains the same), this observation implies that the bonding force between snow particles and the roof surface increases with the increase in temperature in the range of −15 °C to −5 °C. A possible reason is that as the temperature rises, the sintering of snow particles reaches a higher level, resulting in a larger contact area between snow particles and the roof surface.

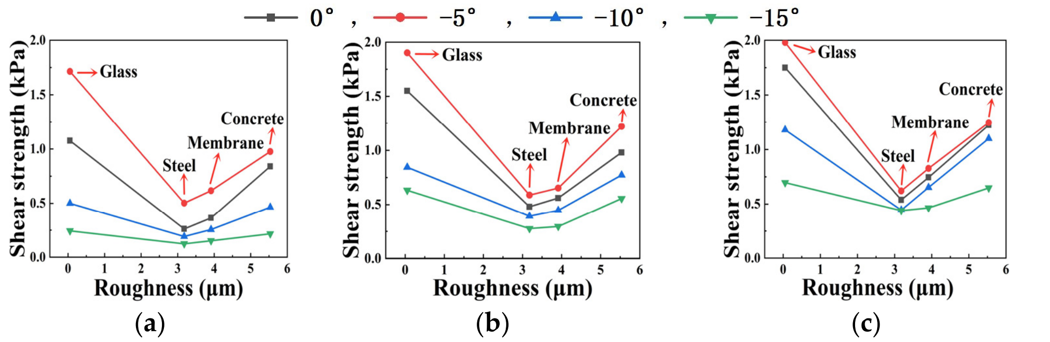


Figure 8. Variation in the shear strength of roof–snow interface with roofing materials: (**a**) 5 cm of snow; (**b**) 10 cm of snow; (**c**) 15 cm of snow.

However, the above-mentioned trend is not applicable to the case of 0 °C. The curve for 0 °C is in between those for −5 °C and −10 °C. This seems to imply that the bonding force reaches its maximum at a temperature near −5 °C when the temperature increases and starts to decrease as the temperature continues to increase. This trend is more obviously observed in Figure 9, where the shear strengths are plotted versus temperature. Unfortunately, the critical temperature for the maximum bonding force is not investigated in the current study.

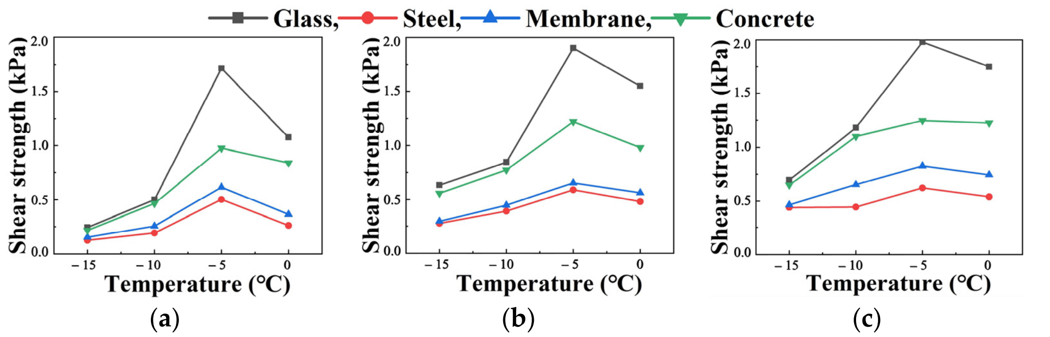


Figure 9. Variation of the shear strength of roof–snow interface with temperature: (**a**) 5 cm of snow; (**b**) 10 cm of snow; (**c**) 15 cm of snow.

Another finding from Figure 9 is that the shear strength of the roof–snow interface at 0 °C is higher than that at −10 °C and −15 °C. This indicates that the shear strength of the roof–snow interface at 0 °C is not negligible and taking the temperature reaching 0 °C as the sole condition for roof snow sliding is not reasonable.

When the shear strengths are plotted versus snow depth (Figure 10), an increasing trend is observed. This is understandable since the friction force is proportional to the normal stress, and the deeper the snow, the higher the normal stress.

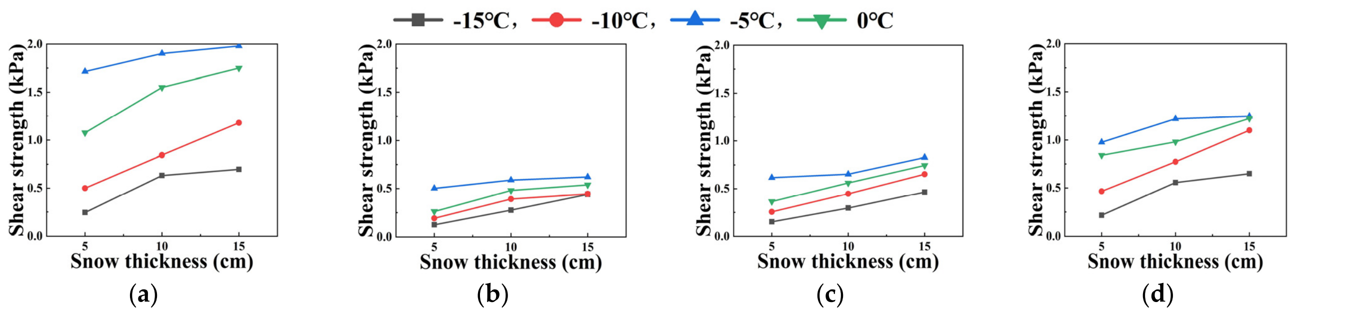


Figure 10. Variation in the shear strength of roof–snow interface with snow thickness: (**a**) glass–snow; (**b**) steel–snow; (**c**) membrane–snow; (**d**) concrete–snow.

4. Conclusions

To possibly reveal the influence of roofing materials on the shear strength of the roof–snow interface, which is essential for deciding the criterion for the occurrence of snow sliding on building roofs, this paper investigates the shear strength of the roof–snow interface by considering four commonly used roofing materials: glass, steel, membrane, and concrete. Two types of experiments are carried out, including critical angle tests, where the angle at which the snow starts to slide off from the roof is tested, and the shearing test, which aims to test the shear strength of the roof–snow interfaces at specific temperatures. The main findings of the current study are as follows:

1. The critical angle for roof snow sliding, as well as the shear strength of the roof–snow interface for the four considered roofing materials, show a U-shape trend with an increase in surface roughness, i.e., the critical angle or the shear strength is higher when the surface is smoother or rougher, and is relatively lower when the roughness is in between.
2. For smoother roof surfaces, the shear strength of the roof–snow interface is dominated by bonding force, while that for rougher roof surfaces is dominated by friction force.
3. The shear strength of the roof–snow surface ranges from 0.15 kPa to 2 kPa for the cases considered in this study and reaches its maximum at certain temperatures near −5 °C for a specific roofing material and snow thickness. The strength decreases when the temperature shifts upward or downward from this peak point.

Author Contributions: Conceptualization, H.M. and F.F.; methodology, X.C. and H.M.; validation, G.Z.; formal analysis, X.C. and H.M; writing—original draft preparation, X.C.; writing—review and editing, H.M.; visualization, X.C.; supervision, H.M. and F.F.; project administration, H.M. and Q.Z.; funding acquisition, F.F., Q.Z. and G.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (grant numbers 51921006, 51927813, 51978207, and 52208157), the Postdoctoral Science Foundation of China (grant numbers 2022M710976 and 2023T160161), Heilongjiang Natural Science Foundation (grant number YQ2021E030), and Heilongjiang Provincial Postdoctoral General Fund (grant number LBH-Z21161).

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: The authors are grateful to three anonymous reviewers for their constructive comments and suggestions on the earlier draft of the paper.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Gow, A.J. On the Rates of Growth of Grains and Crystals in the South Polar Firn. *J. Glaciol.* **1969**, *8*, 241–252. [CrossRef]
2. Sack, R.L.; Arnholtz, D.A.; Haldeman, J.S. Sloped roof snow loads using simulation. *J. Struct. Eng. ASCE* **1986**, *13*, 1820–1833. [CrossRef]
3. Jamieson, J.; Johnston, C. Evaluation of the shear frame test for weak snowpack layers. *Ann. Glacial.* **2001**, *32*, 59–69. [CrossRef]
4. Blackford, J.R. Sintering and microstructure of ice: A review. *J. Phys. D Appl. Phys.* **2007**, *40*, R355. [CrossRef]
5. De Biagi, V.; Barbero, M.; Barpi, F.; Borri-Brunetto, M.; Podolskiy, E. Failure mechanic s of snow layers through image analysis. *Eur. J. Mech.-A/Solids* **2019**, *74*, 26–33. [CrossRef]
6. Taylor, D.A. *Sliding Snow on Sloping Roofs*; Canadian Building Digest; National Research Council Canada: Ottawa, ON, Canada, 1983.
7. Williams, C.J.; Carter, M.; Hochstenbach, F.; Lovlin, T. Sliding snow and ice on buildings: A balance of risk, cost and aesthetics. In Proceedings of the Fifth International Conference on Snow Engineering, Davos, Switzerland, 5–8 July 2004; CRC Press/Taylor & Francis Group: Boca Raton, FL, USA, 2004; Volume 26, pp. 59–64.
8. Mellor, M. A review of basic snow mechanics. In *Snow Mechanics (Proceedings Grindelwald Symposium April 1974)*; IAHS Publication: Oxfordshire, UK, 1975; pp. 251–291.
9. Takakura, M.; Chiba, T.; Ito, T.; Tomabechi, T. On the term controlled by snow load: Practical use of snow sliding on pitched roof. *J. Struct. Constr. Eng. Trans. AIJ* **2000**, *528*, 53–57. [CrossRef] [PubMed]

10. Vallero, G.; Barbero, M.; Barpi, F.; Borri-Brunetto, M.; De Biagi, V.; Ito, Y.; Yamaguchi, S. Experimental study of the shear strength of a snow-mortar interface. *Cold Reg. Sci. Technol.* **2022**, *193*, 103430. [CrossRef]
11. Jelle, B.P. The challenge of removing snow downfall on photovoltaic solar cell roofs in order to maximize solar energy efficiency—Research opportunities for the future. *Energy Build.* **2013**, *67*, 334–351. [CrossRef]
12. Heil, J.; Mohammadian, B.; Sarayloo, M.; Bruns, K.; Sojoudi, H. Relationships between surface properties and snow adhesion and its shedding mechanisms. *Appl. Sci.* **2020**, *10*, 5407. [CrossRef]
13. Bartko, M.; Baskaran, A. Snow friction coefficient for commercial roofing materials. *J. Cold Reg. Eng.* **2018**, *32*, 06017005. [CrossRef]
14. Frederking, R.M.W.; Timco, G.W. Measurement of shear strength of granular/discontinuous-columnar sea ice. *Cold Reg. Sci. Technol.* **1984**, *9*, 215–220. [CrossRef]
15. Timco, G.W.; Weeks, W.F. A review of the engineering properties of sea ice. *Cold Reg. Sci. Technol.* **2010**, *60*, 107–129. [CrossRef]
16. Cao, X.; Mo, H.; Zhang, G.; Zhang, Q.; Fan, F. Experimental Study on Shear Strengths of Ice-Roof Interface Aiming the Study of Roof Snow Sliding. *Front. Earth Sci.* **2022**, *10*, 862134. [CrossRef]
17. Isyumov, N.; Mikitiuk, M. Sliding snow and ice from sloped building surfaces: Its prediction, potential hazards and mitigation. In Proceedings of the 6th Snow Engineering Conference, Whistler, BC, Canada, 1–5 June 2008.
18. Zhou, X.; Zhang, Y.; Gu, M.; Li, J. Simulation method of sliding snow load on roofs and its application in some representative regions of China. *Nat. Hazard.* **2013**, *67*, 295–320. [CrossRef]
19. Zhou, X.; Zhang, Y.; Gu, M.; Sun, L. Simplified Calculation Formula on Sliding Snow Load on Roof. *J. Tongji Univ. (Nat. Sci.)* **2014**, *42*, 1833–1839.
20. *ASTM G115*; Standard Guide for Measuring and Reporting Friction Coefficients. ASTM: West Conshohocken, PA, USA, 2013.