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Orginal Article

Control of building safety through snow load monitoring

Roman Kinasz[1], Wiesław Bereza[1]

[1] *Department of Geomechanics, Civil Engineering and Geotechnics; Faculty of Civil Engineering and Resource Management; AGH University of Krakow; 30 Mickiewicza Av., 30-059 Kraków*
rkinash@agh.edu.pl; ORCID: 0000-0001-6715-9583
bereza@agh.edu.pl; ORCID: 0000-0003-2670-2599

Abstract: Climatic loading in the form of snow load is a significant factor for building structures. This is relevant during the design stage, the execution stage, and especially throughout the operational period. Building owners are legally required to ensure that their roofs are cleared of snow, often raising the question of whether such action is necessary in a particular situation. To address this, various devices have been developed to facilitate the systematic monitoring and measurement of snow load on roofs. These devices measure snow weight either indirectly or directly. The methods for monitoring snow weight and evaluating the effect of snow load on structural safety have been extensively discussed in the literature, considering aspects of structural integrity, operation under harsh conditions, and the economic implications of building management. In this paper, the authors propose an innovative approach to monitoring snow load using snow scales, supplemented by roof deflection measurements with tilt sensors (inclinometers). Such systems not only ensure the safety of the building and its occupants by providing reliable and verified results but also achieve this in a cost-effective manner.

Keywords: snow load, building safety, load monitoring

1. Introduction

According to the Construction Law [17] (Article 61, paragraph 2), *the owner or manager of a construction object is obliged, exercising due diligence, to ensure the safe use of the object in the event of external factors affecting it. These factors may arise from human activity or natural forces, such as (…) intense precipitation, (…) which can result in damage to the construction object or an imminent threat of* such *damage, posing a risk to human life or health, the safety of property, or the environment*. This requirement also applies to snow loads, which are becoming increasingly unpredictable due to weather anomalies [4,5]. Notably, according to the Chief Building Inspector, 90.8% of building disasters in 2022 were caused by random events, with 6.3% attributed to intense precipitation. These figures relate to a total of 663 disasters in 2022 (Fig. 1). In 2021, heavy precipitation accounted for 11.4% of the total 469 building disasters.

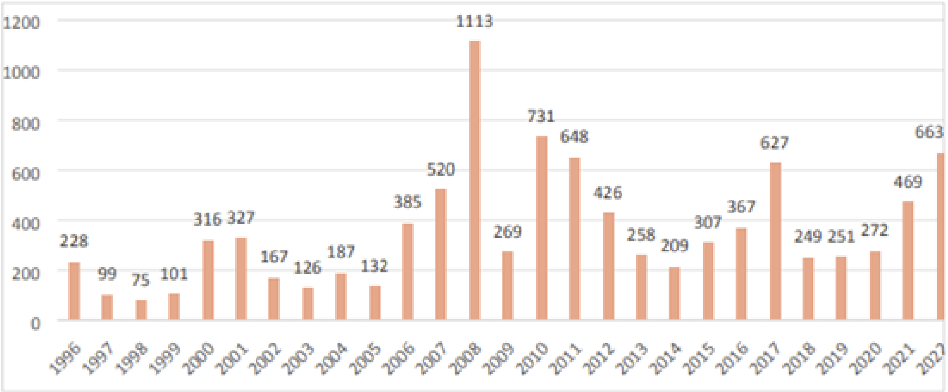

Fig. 1. Construction disasters in Poland in 1995-2022 based on the *Analysis of disasters in 2022*. www.gunb.gov.pl

Although snow load is defined in PN-EN 1991-1-3:2005 Eurocode 1: *Actions on Structures, Part 1-3: General Actions – Snow Load*, along with AC:2009 and NA:2010, it remains insufficiently controlled [3,5,6,7]. For instance, buildings designed before 2006 under PN-80/B-02010 *Loads in Static Calculations* [18] were calculated using lower design snow load values. The snow load standard was revised in 2006 through Az1:2006, introducing a new map dividing Poland into five snow zones and increasing the load factor γ_f from 1.4 to 1.5 [2,12], Fig. 2. Snow load is particularly significant for roof slopes in lightweight halls, where it often constitutes the highest load these structures must withstand. Given the challenges posed by snow load, many designers and construction contractors shift responsibility to building owners and managers, requiring them to monitor snow load during operation through facility use instructions. While a snow removal manual is crucial, the information it contains frequently transfers responsibility to the developer. For example, it is unreasonable to require a user of a new building to remove snow from the roof if the weight exceeds 75% of the standard value, under the threat of voiding the warranty and guarantee.

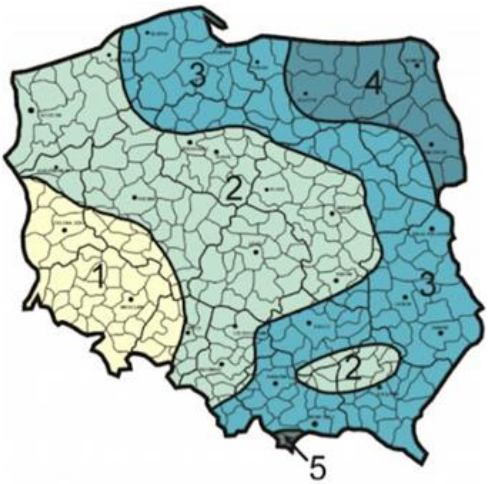

Fig. 2. Division of Poland into ground snow load zones according to PN-EN 1991-1-3:2005/NA:2010 [19]

The issue of monitoring the weight of snow on building roofs becomes even more significant when the economic aspect is considered. Increasingly, structures are being designed with minimal excess load-bearing capacity, while the cost of snow removal from roofs is becoming a critical factor, particularly for large-scale facilities.

2. Measuring the snow load on roofs

Measuring the weight of snow accumulated on roofs is crucial to determining whether the amount of snow is within the limits allowed by the design and whether it poses a danger to the structure. For this reason, it is essential for owners and managers to understand the snow load values adopted during the design phase. These values are typically based on standard regulations or results from laboratory tests, such as aerodynamic tunnel experiments that assess both precipitation and snow redistribution on the roof. This knowledge enables informed decisions regarding snow removal or other necessary interventions.

Determining the actual snow load by measuring its weight is a complex task [5,6]. Snow load varies over time due to changes in temperature, humidity, sunlight, and precipitation. It can be assessed either by measuring the volume of snow (thickness of the snow cover) or through direct measurement (weighing). While measuring the thickness of the snow cover is the simplest approach, it does not provide an accurate indication of the actual impact of snow on the roof's surface. Table 1 presents the standard average values of the volumetric weight of snow and ice depending on their condition [19], with similar values included in the earlier standard [18].

Table 1. Average volumetric weight of snow and ice

Type of snow and ice	Volumetric weight, kN/m^3
Fresh	1.0
Sedimentary (several hours or days after precipitation)	2.0
Old (several weeks or months after precipitation)	2.5-3.5
Wet	4.0
Glaciated	6.0-7.0
Ice (from frozen water)	9.0

So-called snow indicators are still widely used to measure the thickness of snow on roofs. Initially, these devices consisted of scaled poles (mobile or stationary) that allowed the thickness of the snow cover to be read using a linear scale marked on them (Fig. 3a). Measurements were either taken manually for mobile devices or remotely through a mounted camera or monitoring system for stationary devices. Today, ultrasonic or laser snow gauges are more commonly employed (Fig. 3b). These devices use a beam emitted from a sensor fixed at a high level to monitor the thickness of the snow cover. Bespoke solutions for measuring snow thickness are also being developed [1,12]. However, the challenge of accurately determining snow condition and density persists.

To directly determine the volumetric weight of snow, a snowmeter is most commonly used. There are two main types of snowmeters: volumetric and weight-based. In a volumetric snowmeter, a sample of known volume is selected for measurement. However, the selection of the location and depth from which the sample is taken often remains a matter of debate. In contrast, weight-based snowmeters involve weighing snow collected from a specific area. The measuring equipment typically includes a reading device, sampling tray, application, shovel, and carrying case (Fig. 4). A practical issue with this method is the risk of damaging the roofing while scraping snow or ice for weighing, potentially causing leaks and voiding the roofing warranty.

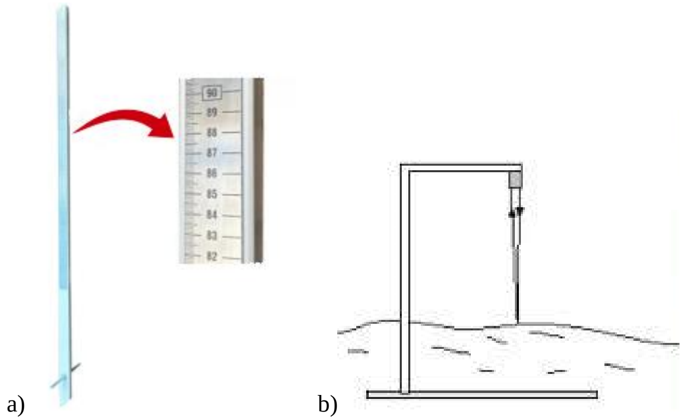

Fig. 3. Snow indicators: classic (a) and ultrasonic (b) as per [1]

Fig. 4. Snowmeter for determining snow load on roofs (illustrations sourced from the manufacturer's materials at www.neostrain.pl)

Given these challenges, the most efficient solution for weighing snow on sloped roofs is the use of snow scales. These devices directly weigh the snow on the roof (Fig. 5). Modern snow scales are typically electronic devices with a known surface area, placed directly on the roof. As snow falls, accumulates, and changes consistency, it exerts pressure on the scales, enabling accurate measurement of the actual weight of the deposited snow. Properly calibrated devices provide reliable data on the current snow load, expressed in kilograms or kN/m² of roof area.

Fig. 5. Snow scale manufactured by KB-Projekty Konstrukcyjne Sp. z o. o. mounted on the roof (own materials)

The measuring system for determining the actual snow load on a roof is not without its limitations. If the measuring zone is too small, there is a risk of snow cover arching over the measuring point, as described in [1] and illustrated in Fig. 6. Laboratory tests conducted by KB-Projekty Konstrukcyjne Sp. z o.o. have demonstrated that arching, as depicted by the line in Fig. 6, occurs for components with dimensions of up to approximately 78 cm. For larger dimensions, natural arching does not occur under typical Polish climatic conditions. This issue does not arise with snow scales measuring at least 1.0 m x 1.0 m, especially when such equipment is used on insulated hall roofs with thermal insulation exceeding 1.00 W/m²K. In these cases, the sealing effect described does not occur, as the device itself does not act as a heat emitter. For uninsulated roofs, no observations or tests have been conducted. Therefore, it can be confidently stated that snow scales of the proposed size will accurately measure the actual weight of the snow cover resting on them.

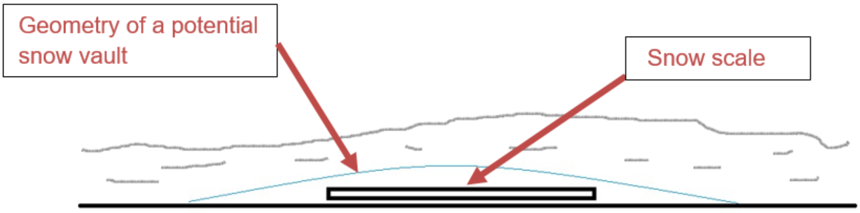

Fig. 6. Proposed snow/ice distribution arrangement for uniform coverage over snow scales [1]

To mitigate potential inaccuracies caused by the formation of overshoots, a mutually controlling system with at least three scales can be implemented, or a system to monitor roof deflection, such as inclinometers, can be introduced. These measures enhance the reliability of measurement results. The system for mutual control of results is discussed later in the article. An innovative approach currently under research involves developing membrane coatings with integrated load cells acting as pressure sensors (Fig. 7). These sensors can be embedded into membranes during production or applied as film coatings adhered to the membrane. This large-scale solution offers protection against unexpected situations arising from snow loads on roof structures.

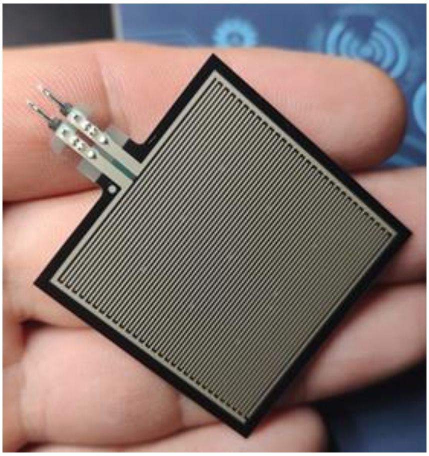

Fig. 7. Pressure sensor used as a load cell (own materials)

3. Monitoring the snow load on the roof

At the design stage of a roof structure, one of the most important steps is the correct assumption of load values, including climatic loads from snow. The accurate selection of parameters for determining this load is particularly important for lightweight constructions, such as industrial halls and warehouses. This is crucial not only for the safety of these buildings but also for the economy of their construction. There is a belief among designers that the snow load assumed for design calculations according to the current standard is a maximum value that, in reality, should never be exceeded. Those who are aware that this is not the case often take the precaution of ordering the owner to remove snow from the roof after every major snowfall. This creates logistical as well as economic problems. Our market survey determined that the average cost of clearing snow from the roof slope in the 2022/2023 season was PLN 4.80 per square metre, and this cost did not include the removal of the snow, which is important for buildings in densely built areas and for buildings with adjacent parking areas. In the 2024/2025 season, this price has already risen to around PLN 9.00 net per square metre, and within large cities even PLN 12.50 net per square metre. Data obtained from owners of hall facilities comparing the costs of a one-off snow clearance service with the costs of monitoring the snow cover on the roof are presented in Fig. 8. With a hall roof area of approximately 4,000 m², the costs of these two activities equalise. This comparison should be treated as an approximation, as in each case additional considerations – such as the presence of snow-bag zones, the existence of skylights and equipment on the roof, the type of covering, and the construction of the roof edge – are significant. Moreover, it is necessary to carry out snow removal according to the design specifications for the roof surface [13,14].

Monitoring snow load on roof structures is not a mandatory element in the modern management of construction facilities. However, it is increasingly utilised due to its importance for both the operational safety of building structures and the economic efficiency of their use. Furthermore, many designers often overlook the implications of a standard provision requiring that snow load calculations account for regions where rain on snow can occur, followed by successive melting and freezing. Such conditions can lead to snow and ice blocking roof drainage systems. Monitoring the weight of snow cover in these scenarios becomes extremely challenging, if not impossible, without the support of direct weighing methods described earlier.

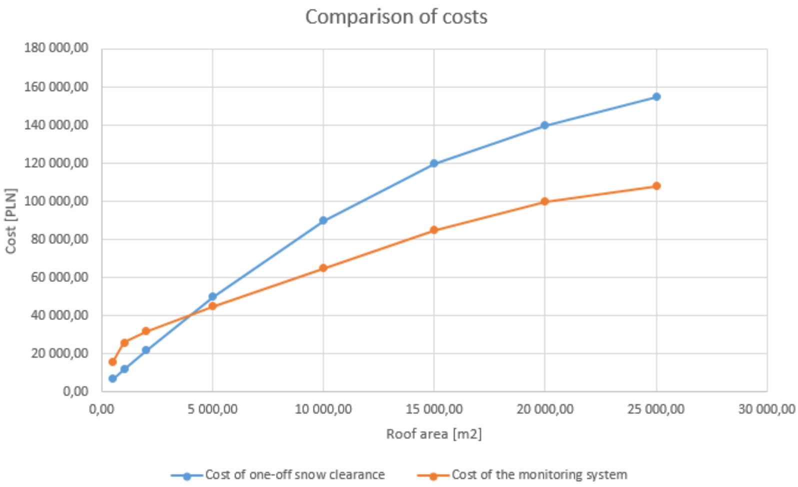

Fig. 8. Comparison of the cost of one-off snow clearing and the cost of the monitoring system

An increasing number of roofs, even when designed in compliance with current standards (e.g., PN-EN 1991-1-3:2005 Eurocode 1: Actions on Structures, Part 1-3: General Actions – Snow Loads [19], along with AC:2009, Ap1:2010, NA:2010), feature complex geometries and carry additional installations. Among these, photovoltaic systems (Fig. 9) are the most common. While these systems do not inherently pose a safety risk to the roof structure, their presence, combined with snow loading and the resulting snow-bagging or shaded zones, can generate excessive loads not accounted for at the design stage. Figure 9 illustrates the placement of a snow scale on a roof equipped with a photovoltaic system.

Fig. 9. Photovoltaic installation mounted on the roof (own materials)

Such roofs are difficult to clear of snow, and as a result, managers of these facilities often avoid snow removal. To address this, various systems have been developed and continue to evolve for monitoring and measuring snow cover parameters, enabling the determination of the weight of snow on the roof structure. This is particularly relevant for large-scale hall buildings and those with lightweight steel roof structures, where snow load is the dominant load.

Another group of buildings for which snow monitoring is recommended includes those with structural layouts not fully compliant with current standard requirements. In such cases, the roof structure should ideally be reinforced. However, due to cost, logistical, or functional constraints, reinforcement may not always be feasible. The alternative is to monitor the actual load acting on the structure and establish procedures to ensure it does not exceed permissible limits. For roofs, this typically involves verifying that the real snow load is below the allowable load (lower than the standard value) specified in the design or an expert opinion. The allowable load corresponds to the load capacity of the structure. The monitoring system tracks snow load levels, and if the safe value is exceeded, snow is removed manually or melted using electrical systems.

Ensuring the safety of the building and its users is paramount. Figure 10 presents a graph, based on literature [10,11], comparing the actual (measured) snow load on the ground at two nearby locations, Tomaszów Lubelski and Zamość. Notably, both sites fall within the same ground snow load zone as defined by PN-EN 1991-1-3:2005/NA:2010 [19].

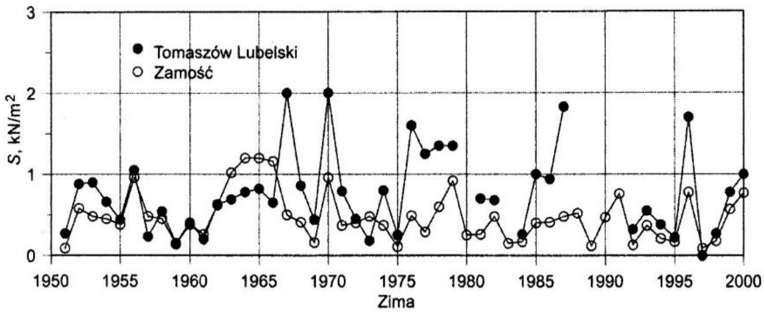

Fig. 10. Comparison of maximum winter snow load values on the ground in Tomaszów Lubelski and Zamość [10]

For this area, the standard value of snow load on the ground according to PN-EN 1991-1-3:2005 should be s_k =1.20 kN/m^2 (Tomaszów Lubelski: 280 m above sea level; Zamość: 212 m above sea level; distance: 42 km). However, this standard value is often exceeded, particularly in Tomaszów Lubelski. The characteristic value of snow load on the ground, as defined by EN [19], has a probability of exceedance of 0.02, excluding exceptional snow loads resulting from precipitation with an extremely low probability of occurrence. Numerous examples of such extreme situations are documented in the literature, prompting discussions about revising the value of this load.

Determining the actual snow load has a significant impact on building safety, especially when the owner or manager lacks extensive knowledge in this area and assumes that a building designed in compliance with standards is immune to all climatic conditions. This belief is reinforced by §204, item 4 *of the Regulation of the Minister of Infrastructure of April 12, 2002, on the technical conditions for buildings and their location*, which states: the *safety conditions of the structure referred to in paragraph 1 are considered to be met if the structure conforms to Polish Standards for the design and calculation of structures* [20].

A separate issue in monitoring snow load is the economic aspect. Awareness by the designer and investor that snow load – unpredictable due to weather anomalies – will be monitored allows for optimal structural design. This ensures compliance with regulations while avoiding excessive safety margins, resulting in significant cost savings, especially in material usage. For example, for roofs of indoor facilities measuring 10,000 m², this approach can save approximately 2-4 kg of steel per square metre (up to 10%), equivalent to 20-40 tonnes of steel. This represents a substantial reduction in investment costs over a building's expected 50-year lifespan. A similar economic argument applies to snow removal.

4. Methodology for monitoring roof building structures

Snow loading on a roof typically causes deformation or bending. This effect is more pronounced in lightweight, steel-framed roofs compared to heavier structures, such as reinforced concrete slab roofs. Furthermore, snow load on a roof is rarely evenly distributed. It depends on factors such as the roof's geometry, slope, presence of attics, the arrangement of equipment and installations, and proximity to higher zones. These factors can lead to snow drifts and snow bags. As recommended in [1], snow load measurements should be conducted in at least three locations on the roof. These measurement zones should be determined by the designer, considering their knowledge of the building structure, the most structurally stressed zones, and areas where the highest snow load is likely to accumulate.

Modern roof snow load monitoring systems are capable of remote operation, transmitting measurements online [15]. Measurements, taken for example every 30 seconds, can be presented graphically to show the current situation or data from a past period. The graph in Fig. 11 illustrates the history of snow load during the low-precipitation 2023/2024 season and following heavy precipitation. Additionally, these monitoring systems can send alerts or signals when pre-established snow load thresholds are exceeded.

Fig. 11. Example of snow load observation history on the roof slope of a facility in Krakow (own materials)

Based on the authors' analysis, the optimal system for monitoring snow load on a building roof consists not only of snow scales but also of a combined system integrating snow scales with inclinometers (Fig. 12a) or level sensors. These additional components monitor the working condition of the roof girders (Fig. 12b). The inclinometers are connected via a cable link to the control panel that displays the results from the snow scales. This design enhances reliability by eliminating potential errors and false alarms. It represents an innovative solution proposed by the authors, implemented on a real site where continuous manual monitoring was not feasible. Similar to the setup illustrated in Fig. 11, a monitoring system comprising snow load sensors and sensors for roof structural behaviour enables observation of the facility's performance over any time interval. Figure 14 provides an example of the correlation between snow load and girder deflection.

Years of data analysis confirm that the proposed online monitoring system operates with great stability, accurately determining snow weight in the controlled area. By duplicating the system and incorporating geometric change sensors, hazardous situations – such as frozen snow obstructing the scale surface or the influence of other loading factors – can be avoided. Expanding the surface dimensions of the scales, not as standalone devices but by shaping the pressure control area, further improves result quality. However, this approach is currently applied (by KB-Projekty Konstrukcyjne Sp. z o.o.) more as part of research projects than as a standard or commonly used technical solution.

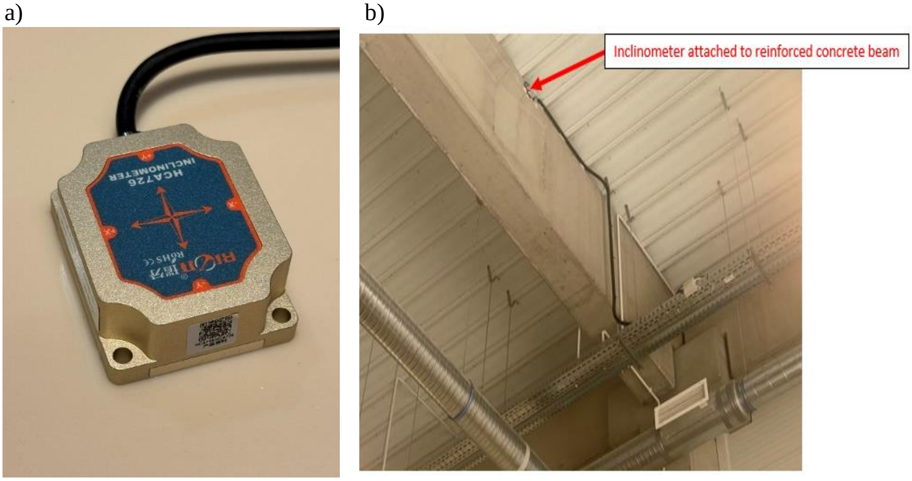

Fig. 12. Installation of the inclinometer sensor on the roof structure beneath the snow scale: (a) inclinometer sensor, (b) sensor location on beam (own materials)

The presented monitoring system is often classified as a SCADA (Supervisory Control and Data Acquisition) system. When integrated with data from the IMGW (Institute of Meteorology and Water Management) and on-site weather stations, such a system can also predict future roof load conditions. This predictive capability is particularly valuable for managers of large construction facilities as part of their planning processes. With this setup, monitoring systems not only report current hazards but also provide insights into their nature – whether the hazard is likely to intensify (if further precipitation is forecasted) or diminish (due to an approaching thaw). Figure 13 illustrates the proposed layout of a SCADA system, designed for autonomous (internal) monitoring, involving the facility owner only when necessary for action.

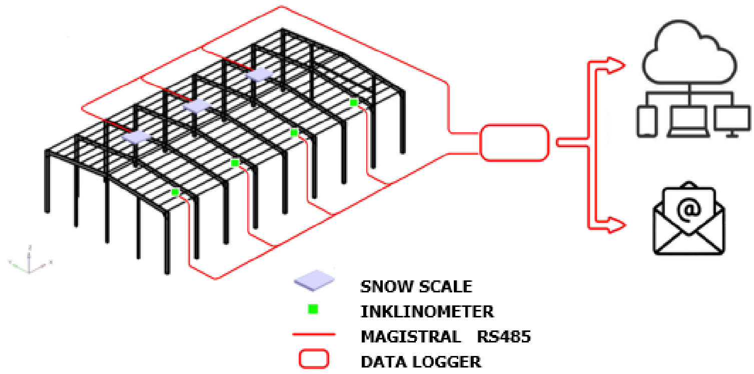

Fig. 13. SCADA system operation diagram for roof snow load monitoring

Fig. 14. Snow load information panel displaying two snow weights and roof structure element deflection for correlating result accuracy (own materials)

5. Snow removal from building roofs

If it is determined (via a monitoring system) or presumed (based solely on observation) that snow accumulation on the roof may pose a threat to the building's structure, it should be removed either partially or entirely. Snow removal is also necessary if accumulated snow hinders the operation of rooftop equipment, as this can disrupt the building's functionality and the proper operation of its installations. However, the snow removal process itself can significantly impact the building and its structural components. Even when performed according to a pre-developed snow removal plan [8,12,13,14], it often introduces additional risks, including:

- damage to the roof covering,
- potential local overloading of the supporting structure,
- danger to lower roof slopes,
- risks to people and property,
- threats to the safety of workers performing snow removal.

For these reasons, it is recommended to minimise snow removal activities unless strictly necessary. This is advisable even when employing "artificial methods" [8], which may require substantial financial investment during construction (e.g., the Snow Out system) or the use of skilled human resources. The Snow Out system, for example, provides maintenance-free snow removal from roof slopes during and after snowfall (Fig. 15) [16]. However, to operate cost-effectively, such systems should incorporate a triggering mechanism linked to snow cover monitoring.

Snow removal is a process that appears simple but, in reality, requires a professional approach. The movement of snow masses must not cause localised structural overloading, and snow must not be stored on the roof. The work itself should use tools that do not damage the structure, and all activities must comply with health and safety standards, as working on icy roofs is extremely hazardous. For building owners or managers, frequent snow removal is a significant administrative challenge. It requires dedicated financial resources as well as formal and logistical planning, particularly for continuously operating buildings. In such cases, a monitoring system proves invaluable, enabling optimal planning and management of resources. These systems ensure snow removal is conducted only when justified, in an economical manner, and adapted to evolving conditions.

Fig. 15. Roof snow removal system based on materials from Klimawent S.A. company [16]

6. Conclusion

The construction market offers a wide range of devices for measuring the weight of snow deposited on roofs, ranging from simple mechanical devices to more advanced electronic systems. However, due to the complexity and variability of this climatic load over time, such devices often produce inaccurate estimates. As a solution, integrated snow weighing systems combined with geometric deformation analysis – achieved by attaching inclinometric devices to the weighing system – are becoming increasingly popular. These systems enable precise measurement of the actual load on the roof while reducing the likelihood of false alarms. They play a crucial role in the maintenance of building structures, offering the advantage of eliminating the need to physically access the roof to check the snow cover. More importantly, they allow remote monitoring of the load and effective task planning to ensure the safety of both the building and its occupants. Internal control mechanisms within such systems, achieved by measuring two independent parameters (snow weight and structural deflections at the load points), enhance the reliability of the measurements.

Automatic snow load monitoring provides building owners and managers not only with a means of ensuring the safe operation of their facilities but also with a way to prevent defects and avoid significant repair costs. By minimising the rate of technical wear and tear, this approach helps maintain the building's structural durability and technical value at the highest level. Systems controlled by both snow scales and inclinometers, supported by internal analysis, ensure a high probability of accurate results throughout the building's operational period.

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