Piezoresistive Sensors for Monitoring Actions on Structures

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Abstract. In the context of climate change, environmental actions on structures are likely to alter in terms of intensities and frequencies of occurrence. To ensure sufficient load-bearing capacity of structures despite these changes, actions may be monitored using structural health monitoring (SHM) systems. Environmental actions involve time-dependent and non-scheduled loads, e.g., wind and snow loads. In current SHM systems, these loads are mostly traced locally. However, local monitoring may cause inaccuracies, as certain load phenomena, such as wind turbulences, or snow accumulations in specific parts of structures, may not be registered. A holistic, global recording of loads acting on structures has rarely been established since a multitude of sensors is cost intensive, and the integration into the building envelope is challenging. This paper investigates slender layered piezoresistive sensors to measure loads resulting from environmental actions, focusing on wind and snow loads. The sensors operate based on changes of externally applied pressure, leading to variations in the electrical resistance of a piezoresistive material. Next to strategies for quantifying structural loads using sensor technology, first, alternatives of force sensors are discussed. Subsequently, the low-cost technical fabrication of the piezoresistive pressure sensors is presented, and implementation, calibration, and validation of the pressure sensors are conducted. Finally, the validation results of the sensors are discussed, and an outlook on future work is presented. In summary, the sensors investigated offer a wide range of applications for monitoring structural actions on surfaces, serving as a basis for estimating the load-bearing capacity of structures reliably.

Keywords: Structural health monitoring (SHM) · Civil engineering · Load monitoring · Piezoresistive sensors · Low-cost force sensors

1 Introduction

In recent years, the use of sensor technology as a diagnostic tool for structural health monitoring (SHM) has significantly increased in the course of climate change and Industry 4.0 [1]. SHM represents an integral tool for the assessment and quality assurance of structures throughout their service life to detect and prevent structural damage at early stages [2]. Simultaneously, measuring and assessing structural parameters using SHM allows to verify design models and to estimate the load-bearing capacity.

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Considering the aspect of uncertain and altering time-dependent environmental conditions as a result of climate change (e.g., wind and snow loads), precise predictions of the structural behavior remains a challenging task [3]. Uncertainties in load assumptions due to changing intensities and frequencies may cause risks, especially contemplating lightweight or slender structures prone to stability or vibrations. Measuring environmental actions for obtaining estimates of the actual load situation can therefore contribute to ensure sufficient safety of structures.

Up to date, sensors for monitoring loads are usually integrated locally in or on structures, as large-scale holistic monitoring is expensive. For example, wind speed is commonly measured utilizing weather stations on roofs of structures [4]. However, these individual local measurements may not adequately capture certain effects, e.g., turbulences associated with a certain structure in case of wind. Transferring to snow loads, e.g. accumulations due to windblown dispersals or sliding may not be covered using local measurements.

In this paper, low-cost pressure sensors are investigated to detect and quantify loads due to wind and snow actions on structures. To this end, low-cost piezoresistive pressure sensors fabricated from conductive copper strips and a semiconducting polymer composite are considered. These slender layered sensors operate based on changes of externally applied pressure, leading to changes in the electrical resistance of the piezoresistive material. Depending on the impact applied, mass-resistance relations are derived by supplying constant power current to the sensors. Next to strategies for quantifying structural actions based on SHM systems, first, the theoretical background of piezoresistive sensors is presented. Subsequently, the technical sensor fabrication and calibration is proposed. Due to their low-cost fabrication and slender layered composition, the piezoresistive pressure sensors are implemented and validated in a holistic, and global monitoring system. Finally, validation results of the sensors are discussed, and key findings are summarized and concluded.

2 Quantifying Loads on Structures

Structural actions and loads, respectively, can be quantified using SHM systems. Typical architectures of SHM systems include sensors, representing physical sensing units, and sensor nodes, i.e., hardware to which the sensors are connected or integrated. Depending on their type, sensors convert physical quantities (e.g., temperature, brightness, or pressure) into electrical signals [5]. Through an analog-to-digital converter, continuous analog electrical signals are processed into discrete digital signals. Subsequently, a microcontroller system transmits the signals wired or wirelessly to a host system or computer, from which the data can be viewed, analyzed, and stored.

For direct measurements of wind and snow loads, force and pressure sensors may be employed, respectively. Generally, the terms force and pressure are used synonymously, assuming that pressures correspond to forces over a defined area [6]. Force measurements at low power supply in ranges suitable for quantifying wind and snow loads are mainly performed by means of (i) *piezoelectric*, (ii) *capacitive,* and (iii) *piezoresistive* pressure sensors [7]:

i. *Piezoelectric pressure sensors* operate based on the piezoelectric effect of crystalline materials, i.e., when loaded, an electrical charge shift proportional to the applied pressure is generated. Piezoelectric sensors are available, e.g., as load cells or flexible thin films made of piezoelectric polymers [8]. Advantageously, no external power supply is required due to the piezoelectric effect. On the other hand, complex electronics are usually required to measure reliably the change in charge [6], and the pressure can cause high and short-termed voltage peaks to be processed. Further, due to the measurement approach, pressure changes of static loads and slowly acting forces, respectively, may rather be detected by capacitive or piezoresistive sensors.
ii. *Capacitive pressure sensors* usually consist of plate capacitors whose capacitance changes as a function of the acting force. Capacitive sensors are able to detect static and dynamic pressure and they exhibit high reproducibility in their measurements. Further advantages of capacitive sensors are high accuracy, flexibility and durability. However, comparable to piezoelectric sensors, the measurement approach of capacitive pressure sensors reveals parasitic effects. Besides, an additionally required electronic driver and measuring circuitry of capacitive sensors lead to further operational expenses additionally to the costly sensor type [6].
iii. *Piezoresistive pressure sensors* function based on changes in the electrical resistance of a material or their electrical contact resistance when pressure is applied. For recording electrical signals proportional to the pressure applied, energy must be supplied to the sensors. Advantageously, piezoresistive sensors record static and dynamic pressures and the electronics required are less complex compared to piezoelectric or capacitive sensors. Furthermore, the fabrication of piezoresistive pressure sensors enables low-cost mass production. Thus, despite potential inaccuracies in their measurements compared to capacitive and piezoresistive sensors, they are widely deployed [9].

The choice of suitable sensors for tracing wind and snow loads depends on the required measuring ranges. In general, the ranges are approximated custom-fit to the expected loads acting on structures based on normative regulations, e.g., Eurocode 1 [10]. Next to the measuring ranges, the operational temperature requirements of the sensors must be considered. For monitoring wind and snow loads, temperatures vary in ranges of winter and summertime, respectively. Since in the present paper, the sensors are to be integrated into building envelopes, intense heating in dependency of the surface color and material has to be considered additionally. Furthermore, especially slender sensors are advantageous as they do not influence the architecture of building envelopes and technically allow easy integration. Additionally, when aiming for holistic monitoring systems, i.e., sensor networks of multiple sensors, the cost-effectiveness of the sensors to economically establish acceptance of users is of vital importance.

Based on the requirements defined, this paper investigates piezoresistive pressure sensors to measure wind and snow loads. Due to their cost-effective fabrication, the ability to measure static as well as dynamic loads, and their slender geometrical dimensions, piezoresistive sensors appear promising for holistic and global monitoring systems. The framework of the sensor system is depicted in Fig. 1. The piezoresistive sensors are integrated into the building envelope. The electrical signals of the sensors triggered by pressure loads are transferred to a computer, where the loads and corresponding structural conditions may be analyzed. In the following, fabrication processes of the piezoresistive pressure sensors and the strategy for converting the electrical signal obtained from the sensors to actual pressures acting on structures is examined.

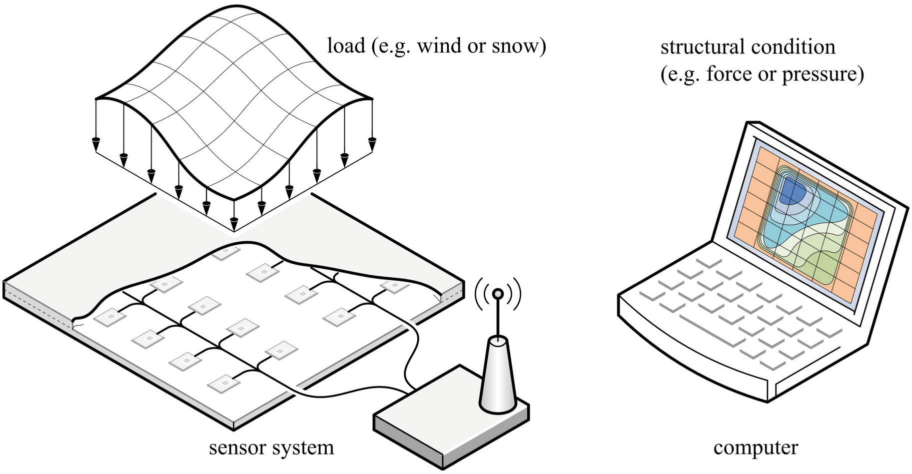


Fig. 1. Framework for monitoring wind and snow loads on structures using holistic and slender piezoresistive sensor systems.

3 Fabrication and Implementation

3.1 Fabrication of Low-Cost Piezoresistive Pressure Sensors

The piezoresistive pressure sensors are fabricated using a semiconducting polymer composite material. The electrical resistance in such composites changes when the distance of conducting particles in the material matrix is varied [11]. One particular polymer composite material used for sensing purposes is "Velostat™". To date, Velostat has barely been explored as sensor type, but it is increasingly being investigated in applications of robotics and healthcare to create flexible and tactile sensors [12]. Several studies exist on modeling the behavior of Velostat, further information may be found in [13].

The pressure sensors fabricated in the present work consist of three layers, as shown in Fig. 2. The first layer comprises an electrically insulating plate on which a conductive line is arranged, formed in a self-adhesive copper tape of 1 cm width and 0.05 mm thickness. The second layer consists of Velostat with a thickness of 0.1 mm. The third layer matches the first layer, however, rotated by 90°. The orthogonal arrangement of copper strips enables a square electrical area of $A_{\mathrm{Vel}} = 1\ \mathrm{cm}^2$. The resistance of Velostat, which changes when applying pressure, is measured via electrical contacts.

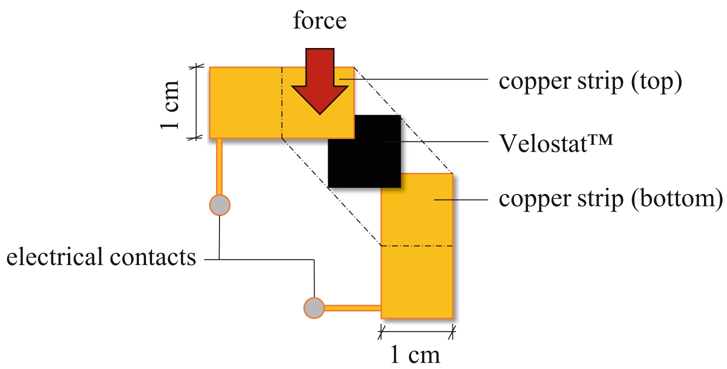


Fig. 2. Composition of the piezoresistive pressure sensors.

3.2 Strategy and Implementation of Data Evaluation

The relationship between physical and digital quantities of the piezoresistive pressure sensors is expressed by means of a transfer function. The transfer function $f(m_i)$ describes the change of sensor resistance $R_{Vel,i}$ in relation to the acting mass m_i. For piezoresistive sensors, the sensor resistance does not change proportionately with the mass, i.e., the transfer function is nonlinear. For obtaining the transfer function, a single pressure sensor with its electrical elements according to Fig. 2 is considered. Details on the corresponding electrical circuit may be found in [14]. The herein derived resistance of the sensor $R_{Vel,i}$ is described by the following equation [13]:

$$R_{Vel,i} = \left(\frac{V_{cc}}{V_{meas,i}} - 1 \right) . R_0, \quad (1)$$

where $V_{meas,i}$ is the measured output voltage of the sensor at time $t = i$, R_0 is an interconnected known resistor, and V_{cc} is the value for the power supply (here: 5.0 V). For developing a mass-resistance relationship (i.e., the transfer function), a logarithmic function $f(m_i)$ utilized for commercial piezoresistive sensors (see [15]) is applied:

$$f(m_i) = \log_{10}(m_i) = a . \log_{10}\left(R_{Vel,i}\right) + b \quad (2)$$

The coefficients a and b of the transfer function resulting from Eq. (2) are obtained during calibration, which is described in the following section.

4 Calibration, Validation, and Discussion of the Pressure Sensors

The calibration setup for investigating the mass-resistance relationship of the piezoresistive pressure sensors is shown in Fig. 3. The gravity of gauged masses starting with 10 g and continuously increasing up to 1.5 kg is introduced into the active sensor area of 1 cm^2, corresponding to a minimum pressure of 0.98 kN/m^2 (0.01 kg/cm^2) and a maximum pressure of approx. 147.10 kN/m^2 (1.5 kg/cm^2).

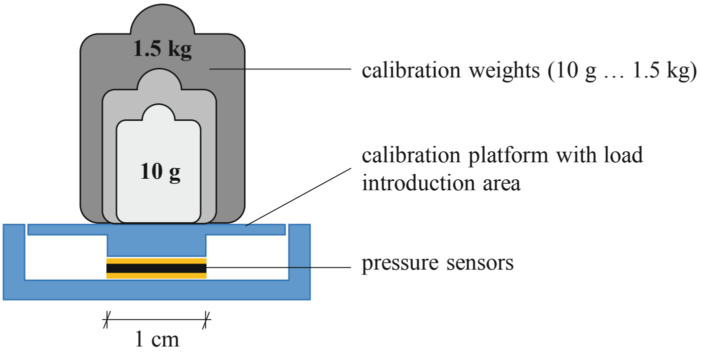


Fig. 3. Calibration setup of the pressure sensors.

For calibration, the output voltages of the sensor $V_{\text{meas,i}}$ corresponding to the applied masses m_{i} are measured. Subsequently, the resistances of the sensor $R_{\text{Vel,i}}$ are determined following Eq. (1) and using an interconnected resistor of $R_0 = 1\ \text{k}\Omega$. Next, the data points of $R_{\text{Vel,i}}$ are approximated by the logarithmic function $f(m_i)$ following Eq. (2). The coefficients of Eq. (2) are retrieved in terms of regression analysis to be $a = -0.565$ and $b = 2.286$. Introducing both coefficients into Eq. (2) yields the following mass-resistance relationship for the Velostat sensors investigated:

$$m_{\text{i}} = \left(\frac{10580}{R_{\text{Vel,i}}}\right)^{\frac{1}{1.77}} \tag{3}$$

Rearranging Eq. (3) with respect to $R_{\text{Vel,i}}$ results in the following transfer function for the piezoresistive pressure sensors:

$$R_{\text{Vel,i}} = 10580 \,.\, m_{\text{i}}^{-1.77} \tag{4}$$

For validation, the pressure sensors are compared to conventional piezoresistive force sensing resistor sensors (FSR) of type RP-S40-ST [15]. As illustrated in Fig. 4, the transfer function obtained from calibrating the Velostat pressure sensor reveals similarity to the transfer function of FSR sensors specified in the datasheet (see [15]). Both transfer functions show strong gradients in the range of low masses, i.e., a small variation of the mass is related to a large change of the resistance value. Contrary, in the range of higher masses, small gradients are apparent, i.e., a large change of the mass leads to a very small modification of the resistance. In the medium mass range, both sensors perform accurate for the evaluation of resistance values.

The transfer function of Eq. (4) is further validated by applying interim mass in the range of the calibrated weights. Depending on the mass, the deviation, i.e., the root mean squared error of the mass-resistance relationship of Eq. (4) varies as shown in Fig. 5. The best results of the transfer function are obtained within the range of 50 g to 400 g with an overall maximum error of 7.5%–8.0%, revealing an appropriate accuracy of the sensors. However, the results demonstrate the higher deviations typical for piezoresistive sensors. For lower ($m_{\text{i}} < 50$ g) and higher measurements ($m_{\text{i}} > 400$ g), the deviations increase and the transfer function may be more imprecise. Based on the validation process, a reliable range of approximately 50 g to 400 g is therefore defined for the Velostat pressure sensors, while for the commercial FSR sensors 50 g to 600 g are detected to be suitable. The ranges are highlighted in Fig. 4 by l_{Vel} and l_{FSR}, respectively. The comparison showcases the good applicability of the low-cost sensors taking a slight decrease of the accurate measuring range into account.

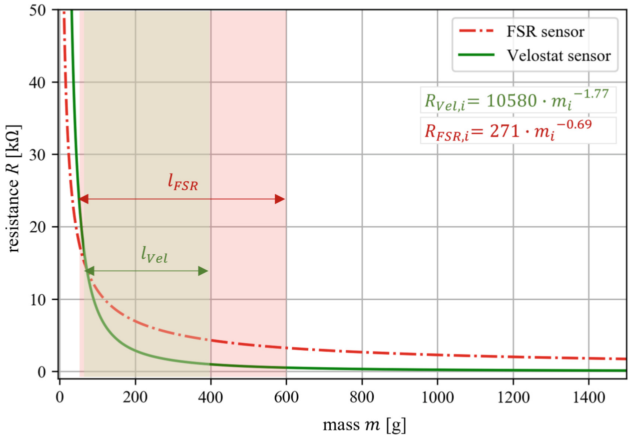
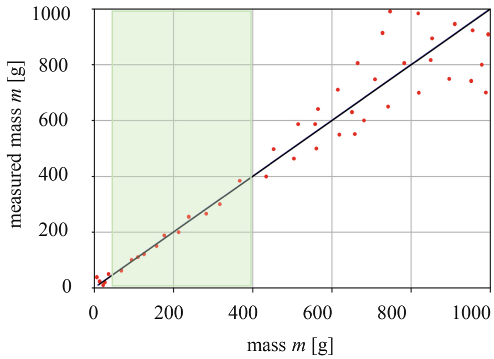


Fig. 4. Transfer function of Velostat sensors compared with the transfer function of FSR sensors of type RP-S40-ST.



mass range	max. deviation [g]	max. deviation [%]
10 g – 50 g	10 g – 8 g	100% – 8.0%
50 g – 400 g	5 g – 30 g	8.0% – 7.5%
400 g – 800 g	30 g – 135 g	7.5% – 16.8%
800 g – 1500 g	135 g – 300 g	16.8% – 20%

Fig. 5. Maximum deviation of measurement results of the pressure sensors during validation.

For a larger-scale validation with 16 sensors, four sensor layers for integrating the sensors are 3D-printed as shown in Fig. 6, using the material Polyethylene terephthalate (PETG). Each layer measures 16 cm × 16 cm combining four previously described sensors. The sensors are arranged in a grid of approx. 8.8 cm × 8.8 cm. To not exceed the precise range investigated in the validation of Fig. 4 (50 g < m_{i} < 400 g), load introduction areas of 2.1 × 2.1 cm are chosen. The fabrication provides an even surface of these pressure areas with the surrounding layer area, such that distributed loads acting to the layer are exclusively introduced into the sensors via the area of $2.1 \times 2.1 = 4.41$ cm^2. Considering 400 g to be detected well by the sensors at maximum, this gives 400 g / 4.41 cm^2 = 8.89 kN/m^2 covering magnitudes of wind and snow loads. In a subsequent data analysis on a computer, the pressures in-between measured values of the sensors can be interpolated and integrated over the total sensor layer area for obtaining the total mass acting to the layers. However, for practical applications it should be noted that the sensor grid size as well as the choice of the load introduction area should be custom-designed depending on the size and the distribution of the loads expected.

To simulate wind or snow loads, a mass of $m = 5.2$ kg, is applied to half of the layer, as shown in Fig. 7a. The mass is introduced only into the net area of the layer surface excluding cutouts for electronics, which become apparent in a closer view of Fig. 6. The measurement results are displayed in Fig. 7b. Pressure in-between sensors are interpolated using cubical polynomials. As the loaded sensor layer area measures $A_{\mathrm{net},2} = 368$ cm^2 (excluding the cutouts for electronics), the mass divided by pressured area, i.e., 5.2 kg / 368 cm^2, gives a mean pressure value of 14.1 g/cm^2 ($q = 1.38$ kN/m^2), which is in agreement to the measured values in Fig. 7b and Table 1. By integrating the measured pressures over the total net area of $A_{\mathrm{net}} = 736$ cm^2, a mass of 5.15 kg is determined, revealing a good approximation of the applied mass. Also, the sensors locate the load well without additional necessity for calibration of single sensors.

It should be noted that the differences in Table 1 not only result from sensor measurement deviations, but from the load application chosen. Unlike wind or snow loads, the total mass is not equally distributed to the sensor layer, if the 4.41 cm^2 sensor areas provide minor irregularities in heights. For instance, if the sensor areas protrude slightly above the adjacent surface, the mass applied will settle completely on these sensor areas leading to higher measured weights.

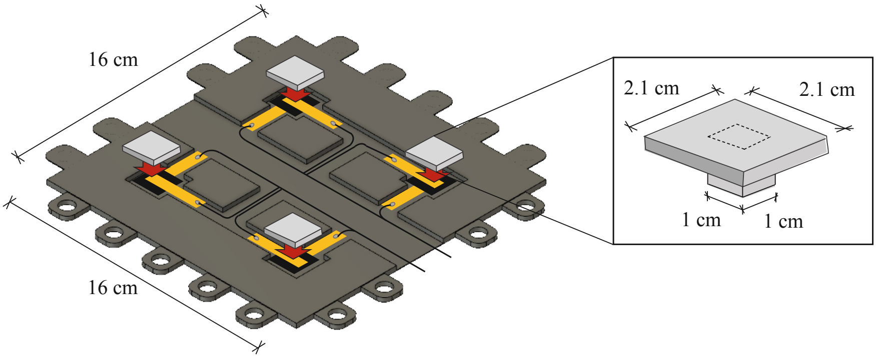


Fig. 6. Layout of one sensor layer for integrating the piezoresistive pressure sensors.

Table 1. Measurements of the eight loaded sensors and deviation from actual mean pressure.

Sensor i	3	4	7	8	11	12	15	16
Pressure [g/cm/^{2}]	10.9	17.4	17.9	11.9	18.4	12.4	10.5	16.9
Deviation [g/cm^2]	−3.2	+3.3	+3.6	−2.4	+4.1	−1.9	−3.8	+2.6

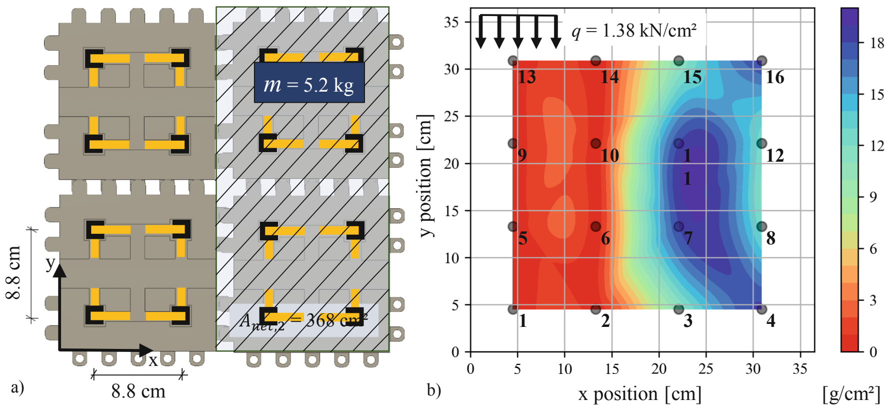


Fig. 7: Validation setup of 16 pressure sensors, a) pressure sensors integrated into four sensor layers stressed by a load of $q = 1.38$ N/cm^2, b) measurements of the sensors.

5 Summary and Conclusions

In the course of climate change, actions on structures are likely to alter in terms of intensities and frequencies of occurrence. To assure sufficient load-bearing capacity of structures within their service life, structural health monitoring (SHM) systems are employed to measure actions as well as structural conditions. However, limited attention has been paid on developing low-cost holistic SHM systems for quantifying actions on structures to date. In this paper, piezoresistive cost-effective, and slender pressure sensors are focused to quantify wind and snow loads acting on building envelopes. The sensors operate based on changes in externally applied pressure, leading to changes in the resistance of a piezoresistive material. In the present work, the operating principles and fabrication of the low-cost piezoresistive sensors are presented and discussed. Subsequently, prototypes of the sensors are calibrated and validated. Further validation tests are performed by arranging the sensors in a grid of custom-designed layers and applying specific load cases. The results demonstrate an acceptable reliability of sensor measures in a range of 50 g to 400 g, the potential of embedding a multitude of sensors into a layer as prospective holistic measuring systems, and the possibility to localize loads accurately within the system proposed. The sensors are suitable for being integrated into building envelopes to measure wind and snow actions on structures. Currently, the sensors still show slight deviations relevant for practical applications. These inaccuracies may be corrected through improved manufacturing and more precise load introduction. Furthermore, in future work, additional investigations of the sensors considering long-term and load drift behaviors, varying environmental conditions, and the durability are to be focused. Besides, extend load and field tests with effects of real wind and snow applications and comparative investigations with conventional, high-fidelity sensors are needed. Additional investigations may also focus on enhancing the sensors to piezoresistive sensor matrices, consisting of several rows and columns of copper strips and reducing the effort for the fabrication of a multitude of individual sensors and their technical components.

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