Performance Evaluation of Flexible Capacitive Sensors on Non-Uniform Surfaces

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ABSTRACT

The use of strain gauges is foundational to structural health monitoring, allowing infrastructure to continuously observe strain, infer stress, and potentially detect fatigue/fracture cracks. However, traditional strain gauges have drawbacks. In addition to being costly, a single-element strain gauge will only detect strain in a single direction and must be mounted on smooth surfaces to ensure good adhesion. Soft Elastomeric Capacitors (SECs) have been proposed as a low-cost alternative to traditional strain gauges while allowing for a broader range of applications. They are flexible and can be modeled with different dimensions based on the monitored structure. Each SEC consists of three layers; the two outer layers act as electrodes and are made of a styrene-ethylene-butylene-styrene polymer in a matrix with carbon black. The inner (dielectric) layer comprises titanium oxide in a matrix with SEBS. The use of the SECs is not limited by the geometry of the surface being monitored, and it can, therefore, be adhered to a variety of surfaces as its flexibility allows it to conform to the irregularity and complexity of the monitored structure. The change experienced by a structure will correlate directly to the change in capacitance observed across the sensor, which can be used to predict the monitored structure's state. While SECs have been studied for applications on various materials, experiments have been limited to adhering the sensor to smooth surfaces. However, concrete structures have various surface finishes that are not uniform, often deriving from an architect's aesthetic desire. This work tests a corrugated SEC through compression tests on concrete samples with different surface finishing to investigate the effect of surface finishing on the SEC-measured strain. Each concrete sample is subjected to loading by a dynamic testing system, and the data collected from the SEC are compared to off-the-shelf resistive strain gauges. The results show that the performance of the cSEC on the different surfaces is not hindered by different concrete finishes, where a high signal-to-noise ratio of 21 dB and low mean absolute error of 22 $\mu\epsilon$ is seen on the concrete specimen with a rough concrete surface. The strain metrics and surface effect on SEC performance are discussed.

Keywords: capacitors, structural health monitoring, concrete strain, surface finishing, sensing sheet, flexible sensors

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1. INTRODUCTION

Advances in health monitoring of structures have seen the development of a variety of sensors and devices. Structural Health Monitoring (SHM) is pivotal in ensuring the safety, durability, and efficient maintenance of infrastructure and buildings. Through the use of advanced sensors and data analysis techniques, SHM systems can detect and diagnose structural damage or deterioration early, enabling timely interventions to prevent catastrophic failures and extend the lifespan of structures 1. This proactive approach to maintenance not only reduces the risk of accidents and associated costs but also optimizes the allocation of resources and minimizes downtime. The strategic placement of sensors on a structure plays a crucial role in the effectiveness of SHM systems.[2] Proper sensor placement ensures comprehensive coverage and sensitivity to the earliest signs of damage, wear, or structural failure, as it directly influences the quality and reliability of the data collected, impacting the system's ability to diagnose potential issues and predict structural performance under various conditions.[3] Many traditional sensors are designed to adhere to non-complex and smooth surfaces for sensing purposes. However, geometrically complex and irregular structures require modifications made to sensors before they can be used. Effective structural monitoring may require that sensors be flexible to conform to the structure being monitored.[4]

Strain sensing on concrete is associated with challenges. The mechanical challenges of sensing strain on concrete stem from its inherent physical properties. Concrete surfaces are uneven, rough, and porous, complicating the installation of strain gauges. These surface irregularities can lead to poor adhesion and incomplete contact between the sensor and the concrete, resulting in inaccurate strain measurements. Special surface preparations are often necessary to overcome these challenges. This may include smoothing the area where the sensor will be placed, using adhesives that can penetrate the concrete's pores to create a secure bond, and employing techniques to ensure that the sensor is in complete contact with the surface despite its irregularities.[5] Moreover, concrete's heterogeneity adds another layer of complexity. It comprises an amalgam of aggregates, cement, and water components. Concrete exhibits variation in its composition that can lead to the localization of stress and strain. When subjected to loading, different concrete parts may experience varying degrees of strain due to differences in material properties and internal structures. This phenomenon poses a significant challenge for strain sensing, especially when using small sensors that only cover a limited area and thus might not accurately capture the overall strain.

The need to attach sensors to large and non-uniform structural geometries has led to the exploration and development of Soft Elastomeric Capacitors (SECs), which are a flexible, cost-efficient sensor capable of strain monitoring.[6] Their flexibility confers adaptability to monitor non-uniform surfaces.[7] However, previous evaluations have been constrained to smooth planer surfaces[8, 9] or smooth surfaces with a single geometric change such as the motioning of welded flanged connections. The catalog of past investigations leaves a critical gap in our understanding of their performance on the more commonly encountered, irregular surface finishing of concrete structures. The present study situates itself within this gap, seeking to assess the behavior of SECs when applied to the variegated textures characteristic of concrete surfaces. This work evaluates SEC performance under these realistic conditions by juxtaposing the outputs from SECs against those from traditional strain transducers.

This work investigates a corrugated SEC (cSEC) of 0.35 mm thickness to understand the effects of non-uniform surfaces on the SEC's performance. Compression loading tests of concrete samples with different surface finishes are used for this investigation. During these tests, the cSEC is attached to concrete specimens with various prepared surfaces, and strain data is recorded by the cSEC. The data obtained is benchmarked against reference strain transducers to ensure accuracy and reliability. Results show that the performance of the cSEC when attached to the investigated surfaces is not significantly affected by their surface textures. These results provide an avenue to investigate the use of SECs on even more complex surfaces where traditional strain gauges cannot be used.

The rest of the paper is structured as follows: section 2 demonstrates SEC technology's background, including the electromechanical model and challenges with sensing on concrete. Section 3 details the experimental setup and procedure applied for the compression test. Section 4 presents and discusses results on the sensing performance. Section 5 concludes the paper.

2. BACKGROUND STUDIES

This section describes the SEC sensor and its electromechanical modeling.

2.1 Soft elastomeric capacitor sensor

The cSEC is manufactured using a styrene-block-ethylene-cobutylene-block-styrene (SEBS) base, integrating titania (TiO_2) within the sensor's dielectric and incorporating carbon black (CB) particles into its electrodes to create a conductive polymer. Detailed manufacturing processes for the cSEC have been previously documented by Liu et al.[9] This SEBS-based cSEC utilizes either filled or doped layers as a capacitor, ensuring a solid mechanical bond as the electrodes and dielectric share the same SEBS polymer matrix. Furthermore, the durability of the cSEC under various weather conditions has been established,[10] highlighting its suitability for long-term, cost-effective monitoring of medium-scale structures. A diagram of a cSEC used in this work is shown in Figure 1(a) and (b), which illustrates the layout of an individual cSEC, measuring 76.2 by 76.2 mm (3 by 3 inches) Figure 1(a). Its shape and dimensions are adaptable, as shown in the schematic in Figure 1(b). This sensor is characterized by its affordability, high elasticity, mechanical strength, straightforward installation, and efficient energy requirements for sensing.

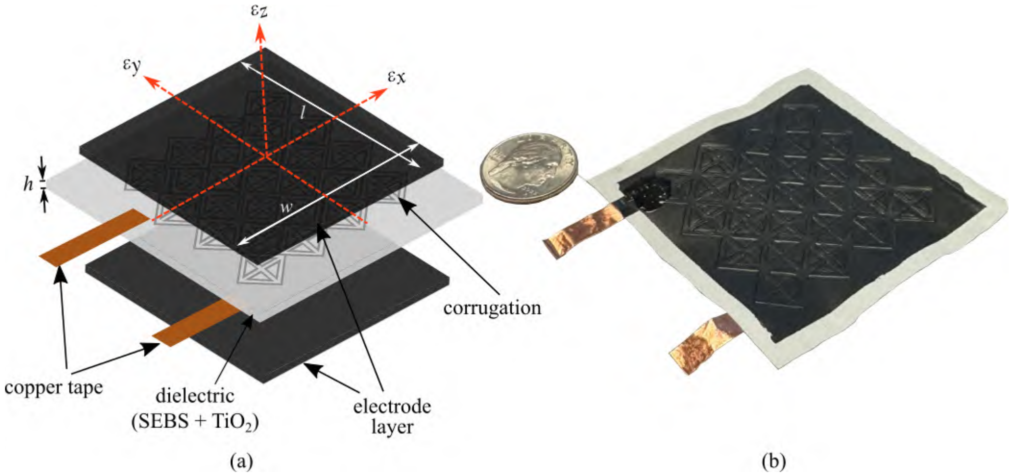

Figure 1. Corrugated soft elastomeric capacitor showing (a) schematic and description of the sensor part, and; (b) the 3 by 3 inches cSEC.

A significant challenge in monitoring concrete using SECs is capacitive coupling between the SEC and the concrete, as detailed by Ogunniyi et al.[8] For an SEC, capacitive coupling between a concrete structure and the SEC amplifies the measured capacitive signal for a given experienced strain. However, this amplification in signal and any significant structure/sensor capacitive coupling is not present when using the cSEC. A detailed investigation of the root cause of this phenomenon is left to future work.

2.2 Electromechanical model

The SEC is used to measure strain through the deformation caused by external forces acting on its surface. This deformation leads to a proportional change in the SEC's capacitance. Such behavior enables the modeling of the SEC as a parallel plate capacitor, which can be described by Eq.(1);

$$C = e_0 e_r \frac{A}{h} \tag{1}$$

In this context, $e_0 = 8.854\text{pF}/m$ symbolizes the permittivity of free space, while e_r refers to the relative permittivity of the polymer, a unitless measure. The term h stands for the dielectric layer's thickness, and the area of the sensor, A, is calculated as the product of its length (l) and width (w), as illustrated in Figure 1. Under the assumption of negligible strain alterations on the surface being observed, the incremental change in capacitance, denoted as ΔC, can be derived by applying differentiation to Eq.(1) to arrive at Eq.(2).

$$\frac{\Delta C}{C_0} = \left(\frac{\Delta l}{l_0} + \frac{\Delta w}{w_0} - \frac{\Delta h}{h_0} \right) = \varepsilon_x + \varepsilon_y - \varepsilon_z \tag{2}$$

ΔC signifies the variation in capacitance of the Strain-Sensitive Capacitor (SEC) as a result of strain, whereas C_0 is the baseline capacitance value of the SEC. The variables ε_x, ε_y, and ε_z represent the strain along the x, y, and z axes, respectively. The SEC is utilized in the $x - y$ plane for the purpose of monitoring surface strain. Under the assumption of plane stress conditions and the application of Hooke's law,

$$\varepsilon_z = -\frac{\nu}{1-\nu}(\varepsilon_x + \varepsilon_y) \tag{3}$$

By integrating the expression from Eq.(3) into Eq.(2), one can deduce the capacitance response of a free-standing SEC:

$$\frac{\Delta C}{C_0} = \frac{1}{1-\nu_0}(\varepsilon_x + \varepsilon_y) = \lambda_0(\varepsilon_x + \varepsilon_y) \tag{4}$$

v_0 represents the Poisson's ratio of the Strain-Sensitive Capacitor (SEC), and λ_0 denotes the gauge factor of the SEC.

$$\frac{\Delta C}{C_0} = \lambda_0(\varepsilon_x + \varepsilon_y) \tag{5}$$

$$\varepsilon_m = (\varepsilon_x + \varepsilon_y) \tag{6}$$

$$\frac{\Delta C}{C_0} = \lambda(\varepsilon_x + \varepsilon_y) \tag{7}$$

$$\frac{\Delta C}{\lambda C_0} = \varepsilon_m \tag{8}$$

where ε_m is the strain on the monitored surface.

3. METHODOLOGY

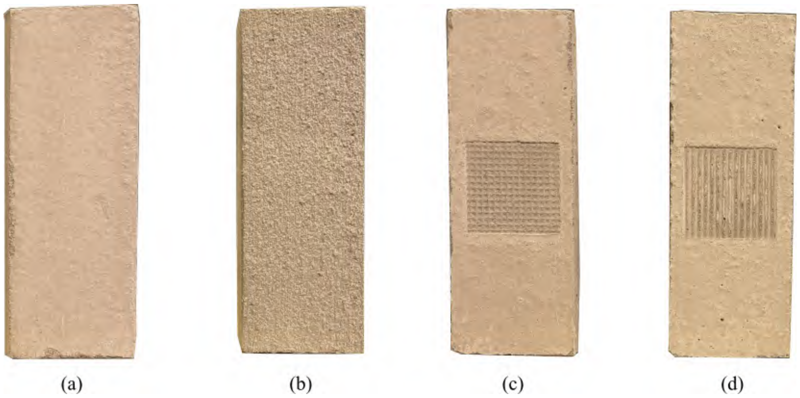

Figure 2. Four concrete specimens with different surface finishes for adhering the cSEC, showing: (a) smooth finish; (b) rough surface finish; (c) dot grid finish, and; (d) vertical groove finish.

3.1 Concrete surface preparations

The concrete specimen is an unreinforced concrete section, with dimensions 0.305 × 0.102 × 0.102 m (4 × 4 × 12 in) Figure 2(a)-(d). The concrete was made using a 27 MPa (4000 psi) strength concrete mix, 3.5 L of water per 36.3 kg (80 lb) of concrete mix, and has an approximate density of 2014 kg m^{-3} (125.73 lb ft^{-3}) on each sample. Surface finish pattern fabrication using 3D printing technology was immediately placed on the concrete while still in the mold to create the test patterns in the concrete specimen (Figure 2(a) and (b). Figure 2(c) shows a concrete with a rough surface finish, while Figure 2(d) is the sample with a smooth surface finish. The specimens were allowed to be cured for at least seven days before testing since the only strain was acquired during the test, and the strength of the specimens was not the focus of the tests.

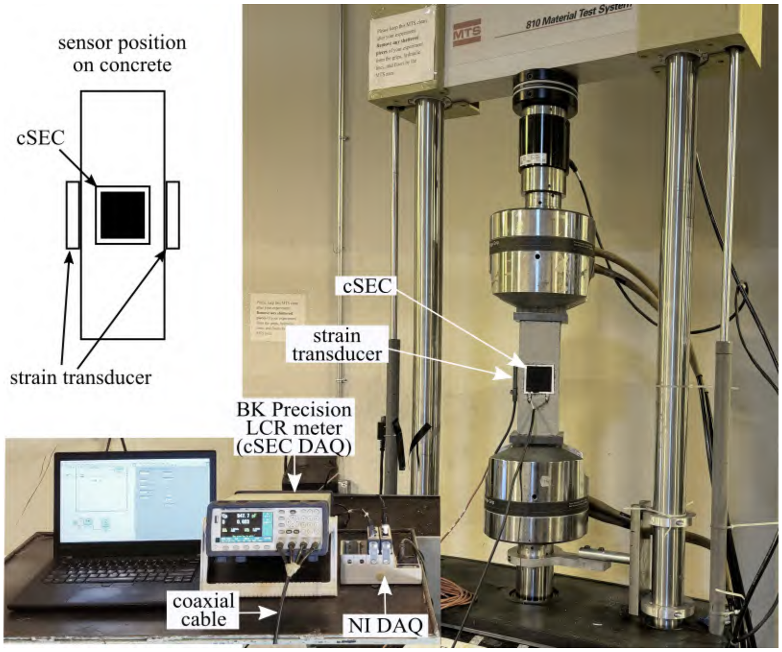

Figure 3. Figures showing the experimental setup for the compression test using dynamic test system with the data acquisition system.

3.2 Concrete compression test

The effect of concrete sample surface texture on the cSEC of thickness 0.35 mm was characterized and assessed through a series of compressive tests conducted on a closed-loop servo-hydraulic testing machine (MTS with Model No. 609.25A-01) with a maximum loading capacity of 250 kN. Figure 3 shows the overall experimental configuration.

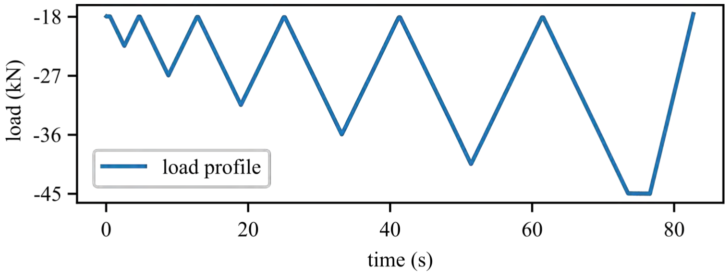

Figure 4. Loading protocol for the compression tests on concrete specimen with (a) showing cyclic loading for three cycles, and; (b) triangle loading with increasing peaks.

Before the dynamic test, the concrete sample was pre-loaded to -45 kN to prevent signal drift caused by electrical interference with the dynamic testing machine and the initial settling of the concrete specimen under compression. From the compressed state of -45 kN, tests were performed by subjecting each cSEC-concrete specimen to the triangle load profile shown in Figure 4. A strain transducer (ST350 350-Ω strain transducer by BDI) was installed on the side surface to benchmark results. cSEC data were collected using an LCR (model 891 by BK Precision) at a sampling frequency of 45 S/s, and the data measured by the strain transducer was recorded using the analog input module, National Instruments NI-9237 at a sampling frequency of 1600 S/s. All compression tests were conducted in the laboratory under a constant temperature condition and were repeated at least three times for each specimen.

4. RESULTS

Figure 5 presents the cSEC-measured strain obtained using the sensor's electromechanical model when subjected to the loading protocol in Figure 4. The measured strain is validated against two reference strain transducers placed on the side of the concrete specimen. The cSEC experiences the highest strain peaks on the concrete with a smooth surface Figure 5(a), indicating a superior sensitivity. This is likely due to more complete contact between the sensor and the monitored surface, allowing for efficient strain transfer from the concrete to the sensor and, consequently, a larger capacitance change. The rough surface, Figure 5(b), characterized by an irregular and uneven texture, exhibits lower strain peaks than the smooth surface. This reduced peak height suggests that the sensor's contact with the surface is less consistent, leading to a slightly diminished sensitivity. The rough texture likely creates air gaps or points of non-contact that mitigate the capacitance response. On a concrete sample with a smooth surface finish, the cSEC demonstrated excellent agreement with the reference transducer, as evidenced by a high Signal-to-Noise Ratio (SNR) of 26.2 dB, Root mean square error (RMSE) of 5.15 $\mu\epsilon$, and a low Mean Absolute Error (MAE) of 8 $\mu\epsilon$, indicating precise strain measurement with minimal noise interference. For the rough surface finish specimen with more exposed aggregates, the cSEC's performance slightly declined with an SNR of 19.4 dB, RMSE of 24.4 $\mu\epsilon$, and an MAE of 33 $\mu\epsilon$, suggesting a moderate impact of surface roughness on measurement accuracy. The metrics used to define the result are presented in Table 1, showing the SNR, RMSE, and MAE values obtained from the compression tests using the average of the strain transducer as true value.

Table 1. SNR, MAE, and RMSE values from compression test on all the surface types investigated

surface type	SNR	RMSE	MAE
smooth	26.2 dB	5.15 $\mu\epsilon$	8 $\mu\epsilon$
rough	19.4 dB	24.4 $\mu\epsilon$	33 $\mu\epsilon$
dot grid	25.7 dB	9.41 $\mu\epsilon$	16 $\mu\epsilon$
vertical groove	22.1 dB	11.5 $\mu\epsilon$	23 $\mu\epsilon$

The cSEC on the dot grid's surface shows strain levels that are lower than the one on the smooth surface but higher than the rough surface when compared to the reference strain transducer, as shown in Figure 5(c). This indicates a moderate level of sensitivity. The structured pattern of the dot grids may create periodic contact points that enhance the sensor's ability to detect strain. However, the overall contact area is less than the smooth surface's, resulting in intermediate peak values. Lastly, the vertical groove surface (Figure 5(d)) presents relatively high strain peaks, suggesting that the grooves allow for good sensor contact, albeit less than the smooth surface. The regular pattern of grooves ensures that the sensor has repeated and predictable contact with the surface. In the case of the concrete surface with a dot grid finish Figure 5(c), the cSEC recorded an SNR of 26.7 dB, RMSE of 9.41 $\mu\epsilon$, and an MAE of 16 $\mu\epsilon$, showing a capability to maintain a good quality of strain measurement despite the textured finish. Finally, on the concrete with a vertical groove finish (Figure 5(d)), the cSEC's signal SNR was observed at 22.1 dB, RMSE of 11.5 $\mu\epsilon$, and with an MAE of 23 $\mu\epsilon$, which points to a reasonable accuracy of the cSEC in measuring strain on patterned surfaces. Overall, the cSEC sensor consistently provided a reliable measure of strain across different concrete surface textures, albeit with varying degrees of precision as indicated by the metrics in Table 1. A noticeable decrease in strain measured by the cSEC is observed on each surface at the last loading cycle. This decrease could be due to factors like localization of strain

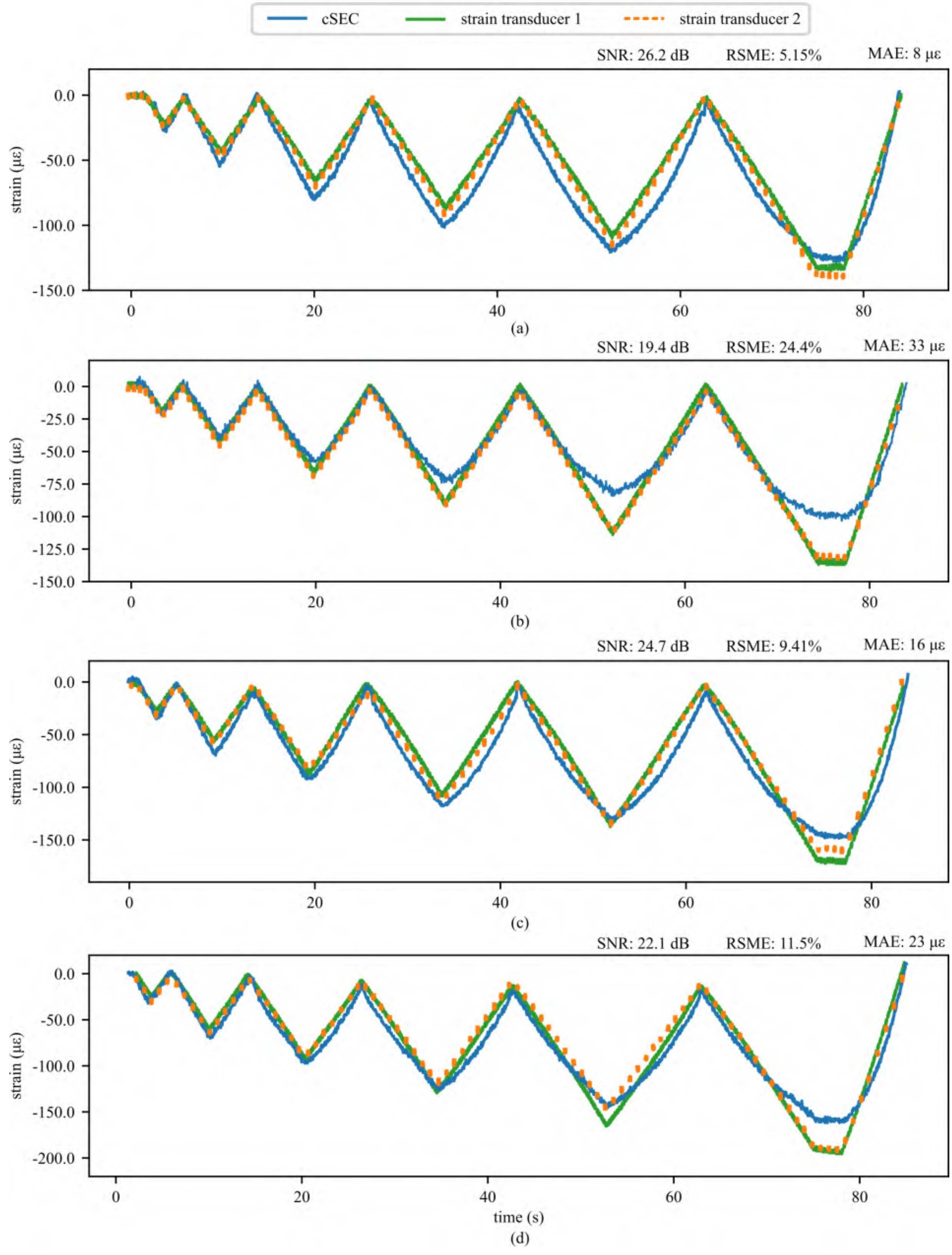

Figure 5. Strain measured by the cSEC compared to two strain transducers from concrete of (a) smooth surface, (b) rough surface, (c) dot grid finish, and; (d) vertical groove surface during the compression tests.

on the concrete surface or the capacitive nature of the sensor itself, which will be further investigated. However, the results showed that strain is diminished as the contact with the monitored surface decreases; however, the sensor's flexibility allows sufficient strain to be sensed even on a rough surface.

5. CONCLUSION

The study in the paper evaluates the performance of Soft Elastomeric Capacitor (SEC) sensors on non-uniform surfaces, particularly concrete with various finishes. These SECs are a flexible, cost-effective alternative to traditional strain gauges, capable of large-area strain monitoring. The work includes a characterization of the SECs' responsiveness to strain on different concrete finishes. The study found that SEC sensors maintained a high level of performance across different surface textures, with a high signal-to-noise ratio and low error metrics, indicating minimal noise interference and precise strain measurement capabilities. The SEC sensor demonstrated excellent agreement with the reference transducer on a smooth concrete surface, indicated by a signal-to-noise ratio (SNR) of 26.2 dB, RMSE of 5.15 $\mu\epsilon$, and a mean absolute error (MAE) of only 8 $\mu\epsilon$. The cSEC's performance slightly declined for the rough surface finish specimen but remained robust with an SNR of 19.4 dB, RMSE of 24.4 $\mu\epsilon$, and an MAE of 33 $\mu\epsilon$. These results are as expected for a good-performing SEC. These findings underline the SEC's potential as a flexible and reliable option for structural health monitoring, capable of accurate strain measurement across various surface textures. The SEC could advance the field of SHM by providing a versatile tool for monitoring complex structures with varying architectural finishes.

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