PERFORMANCE EVALUATION OF FLEXIBLE CAPACITIVE SENSORS ON NON-UNIFORM SURFACES

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OUTLINE

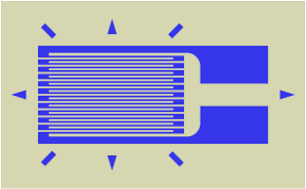
- Motivation
- Background
  - What we have done
  - Where we are
- Current work and results
- Conclusion

MOTIVATION

- Static and dynamic strain could result into Structural failures

- Surface strain sensors, such as linear variable differential transformers, Fiber Bragg gratings, and resistive strain gauges, have seen significant use for monitoring concrete infrastructure

- Limited by area covered



Resistive strain gauge

Fiber Bragg gratings

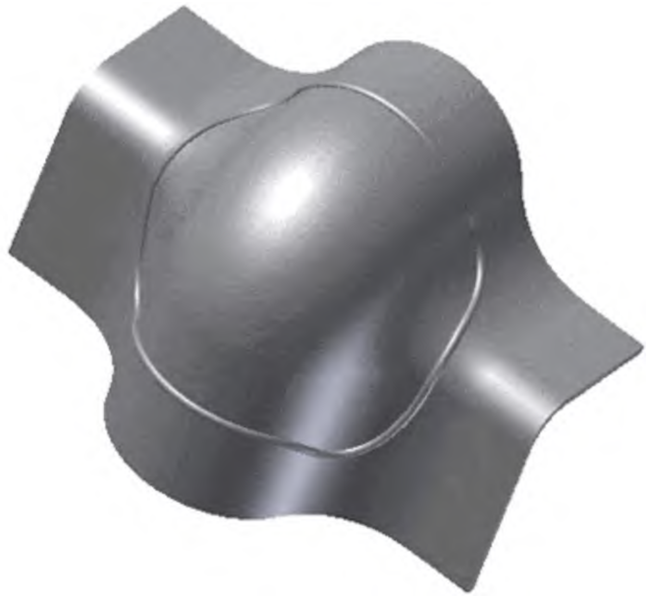
linear variable differential transformers

https://i0.wp.com/theconstructor.org/wp-content/uploads/2016/10/structural-failures-of-concrete-structures.jpg?fit=675%2C364&ssl=1
https://www.geokon.com/Bridges https://www.rp-photonics.com/bg/products/hbk_fibersensing/fiber_bragg_gratings.jpg
https://en.wikipedia.org/wiki/Strain_gauge

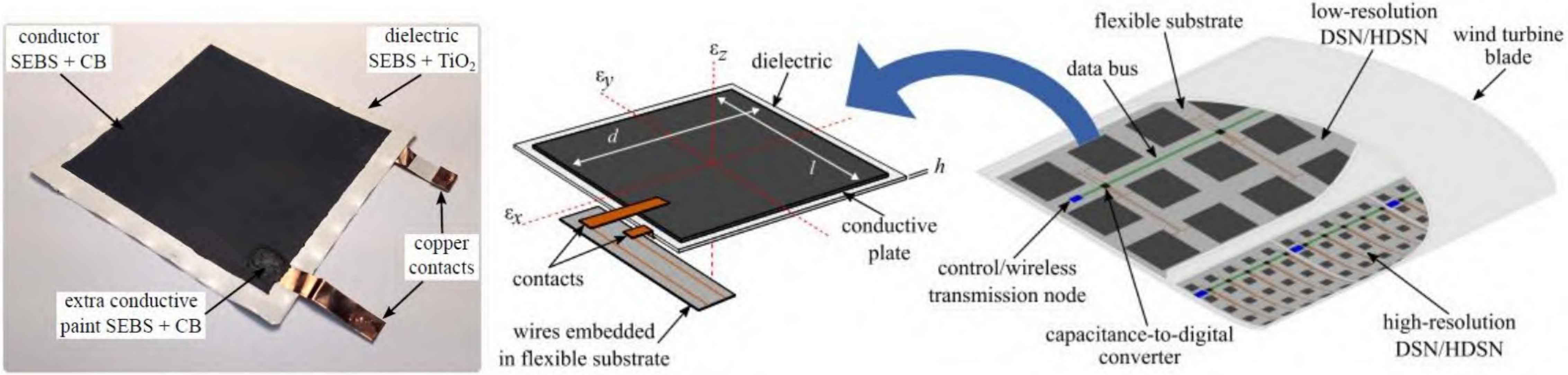
MOTIVATION

- Non-uniform surfaces

- Geometrically complex surfaces



BACKGROUND: SOFT ELASTOMERIC CAPACITOR

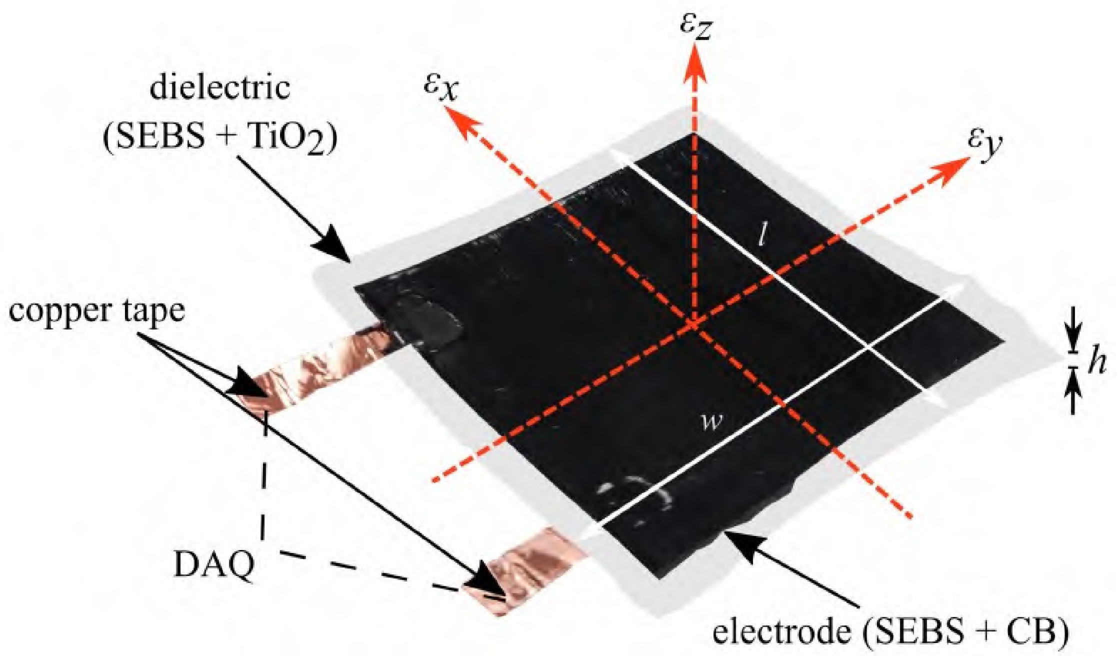


The sensor has the following features:

- Low cost,
- Great ultra flexibility,
- Mechanical robustness,
- Ease of installation, and
- Low power consumption required for sensing

Laflamme, Simon, et al. "Soft capacitive sensor for structural health monitoring of large-scale systems." Structural Control and Health Monitoring 19.1 (2012): 70-81.

SENSING PRINCIPLE



Functions as a parallel plate capacitor

- Respond to changes in the sensor geometry
- Linearly in sensor area and inversely to thickness
- Changes in geometry corresponds to change in capacitance

Laflamme, Simon, et al. "Soft capacitive sensor for structural health monitoring of large-scale systems." Structural Control and Health Monitoring 19.1 (2012): 70-81.

BACKGROUND: ELECTROMECHANICAL MODEL

$$C = \epsilon_0 \epsilon_r \frac{lw}{h}$$

Parallel plate capacitor

$$\nabla C = \epsilon_0 \epsilon_r \left(\frac{l}{h} dw + \frac{w}{h} dl - \frac{lw}{h^2} dh \right)$$

Gradient w.r.t. deformation

$$\Delta C = \epsilon_0 \epsilon_r \left(\frac{l \, \Delta w}{h} + \frac{w \, \Delta l}{h} - \frac{lw \, \Delta h}{h^2} \right)$$

Assume uniformity of deformation

$$\frac{\Delta C}{C_0} = \frac{\Delta w}{w} + \frac{\Delta l}{l} - \frac{\Delta h}{h}$$

Normalize difference in capacitance

BACKGROUND: ELECTROMECHANICAL MODEL

$$\frac{\Delta C}{C_0} = \frac{\Delta w}{w} + \frac{\Delta l}{l} - \frac{\Delta h}{h}$$

Normalized difference in capacitance

$$\frac{\Delta C}{C_0} = \varepsilon_{\mathrm{w}} + \varepsilon_{\mathrm{l}} - \varepsilon_{\mathrm{h}}$$

Definition of strain

$$\varepsilon_{\mathrm{h}} = -\frac{\nu}{E}(\sigma_{\mathrm{l}} + \sigma_{\mathrm{w}}) = -\frac{\nu}{1-\nu}(\varepsilon_{\mathrm{w}} + \varepsilon_{\mathrm{l}})$$

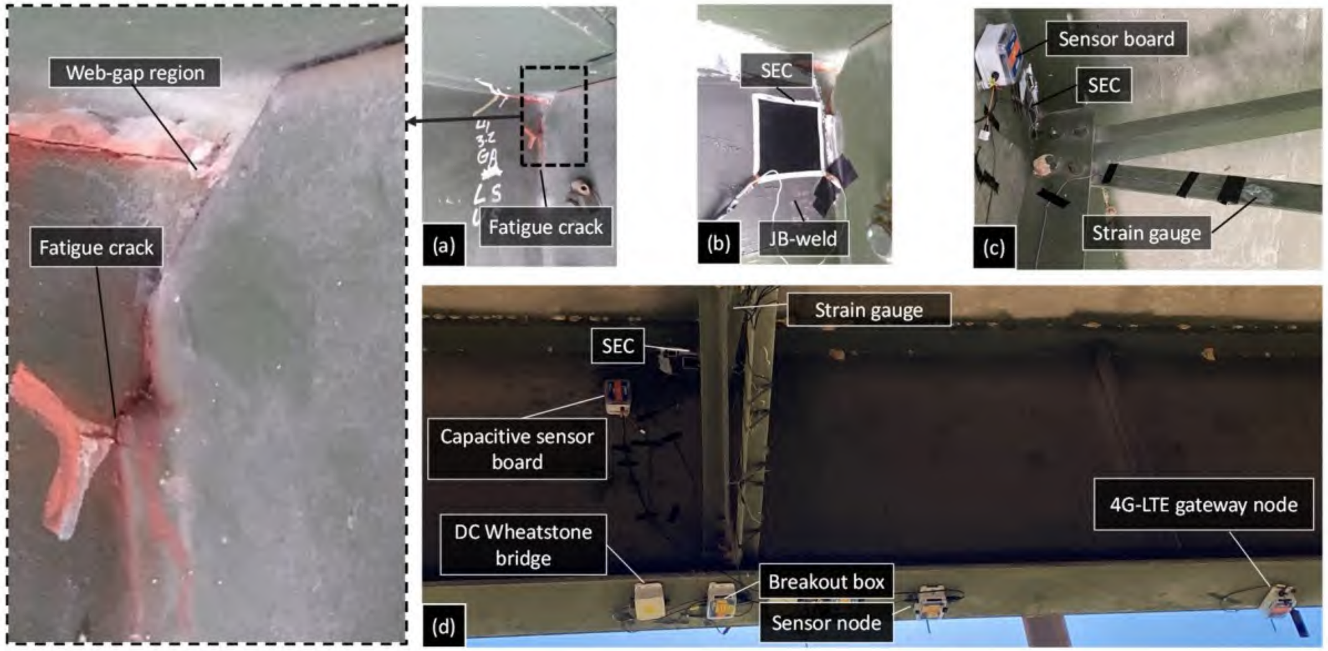
Plane stress assumption

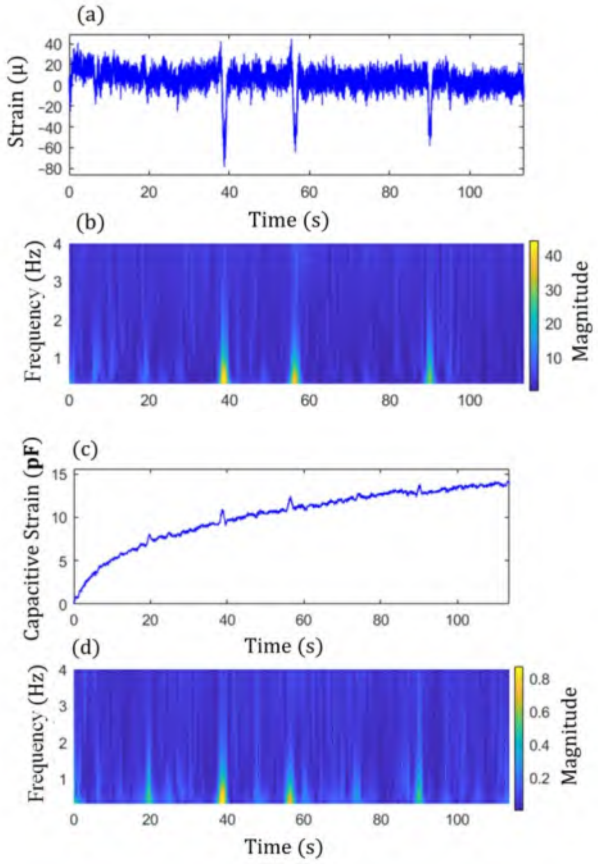
$$\frac{\Delta C}{C_0} = \frac{1}{1-\nu}(\varepsilon_{\mathrm{l}} + \varepsilon_{w})$$

Capacitance in areal deformation

BACKGROUND

Structural health monitoring of fatigue cracks for steel bridges with wireless large-area strain sensors

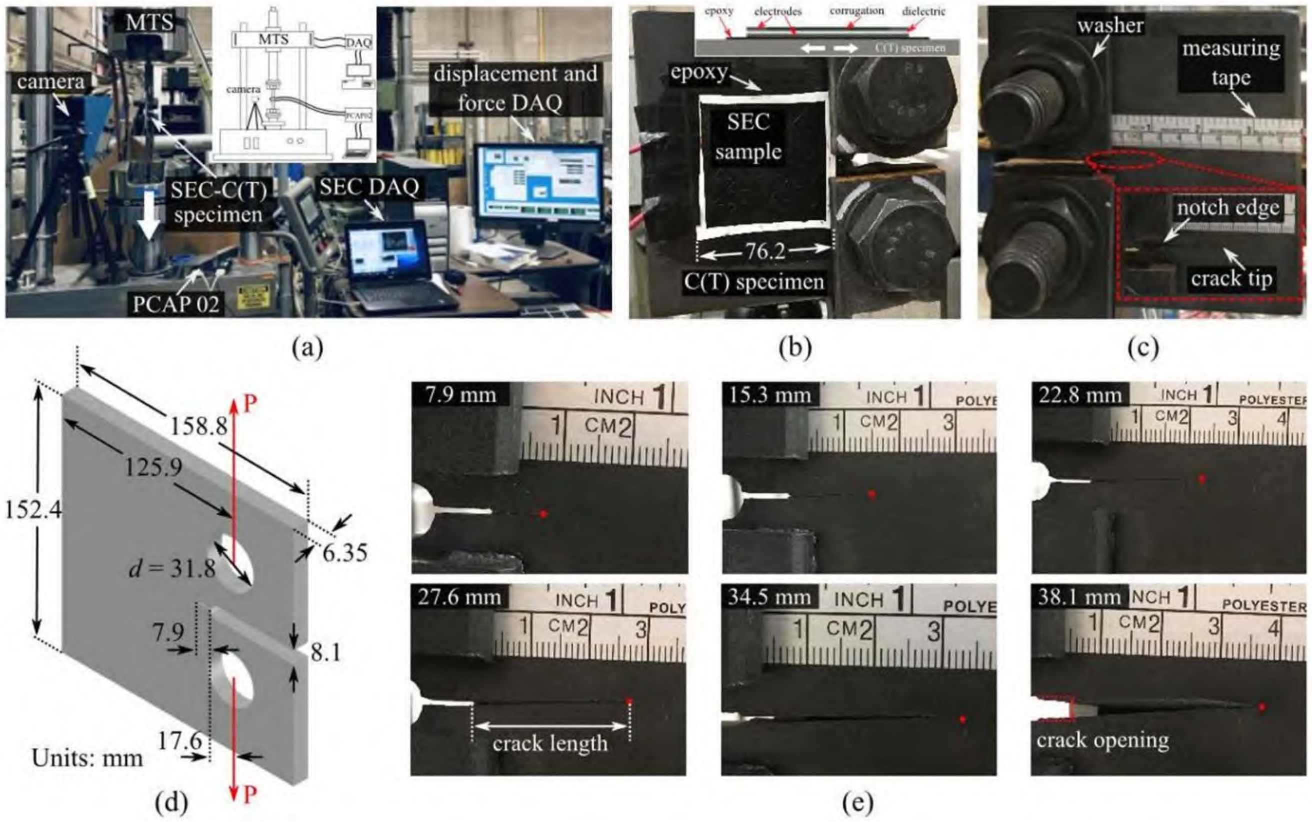




Taher, S. A., Li, J., Jeong, J.-H., Laflamme, S., Jo, H., Bennett, C., Collins, W. N., and Downey, A. R. J., "Structural health monitoring of fatigue cracks for steel bridges with wireless large-area strain sensors," Sensors ***22****, 5076 (jul 2022)*

BACKGROUND

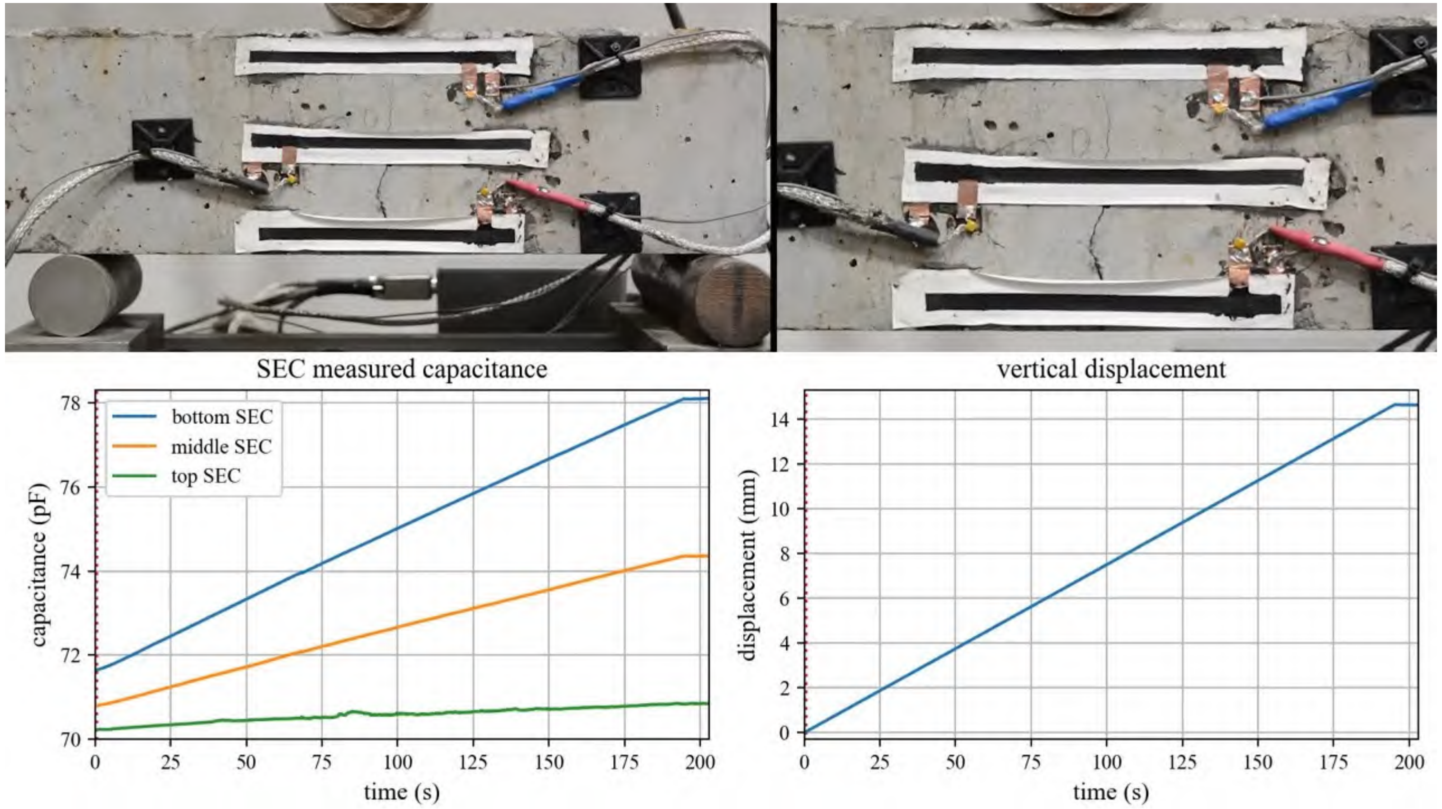
Investigation of surface textured sensing skin for fatigue crack localization and quantification



Liu, Han, et al. "Investigation of surface textured sensing skin for fatigue crack localization and quantification." Smart Materials and Structures 30.10 (2021): 105030.

BACKGROUND

Concrete Crack Detection and Monitoring Using a Capacitive Dense Sensor Array



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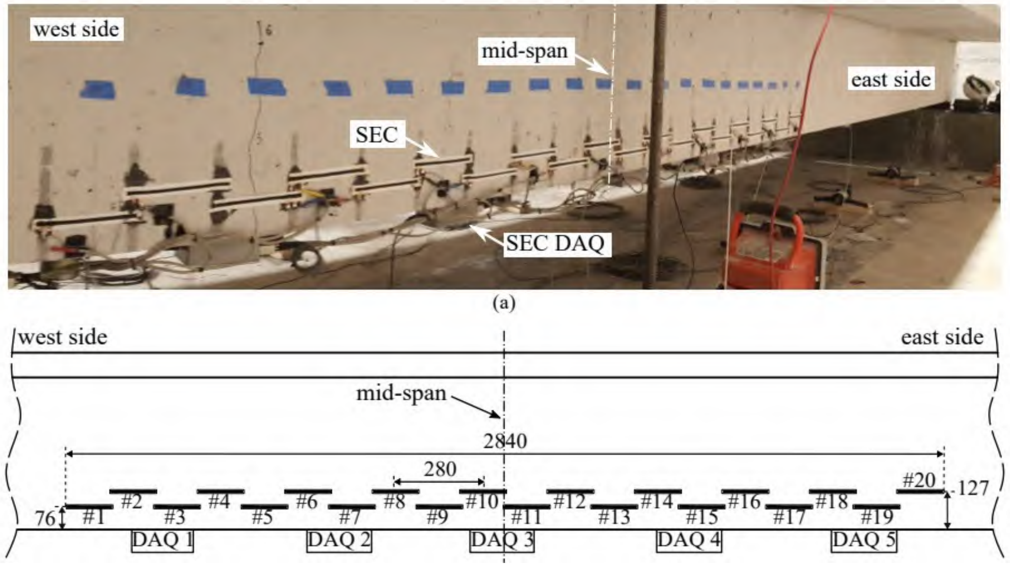
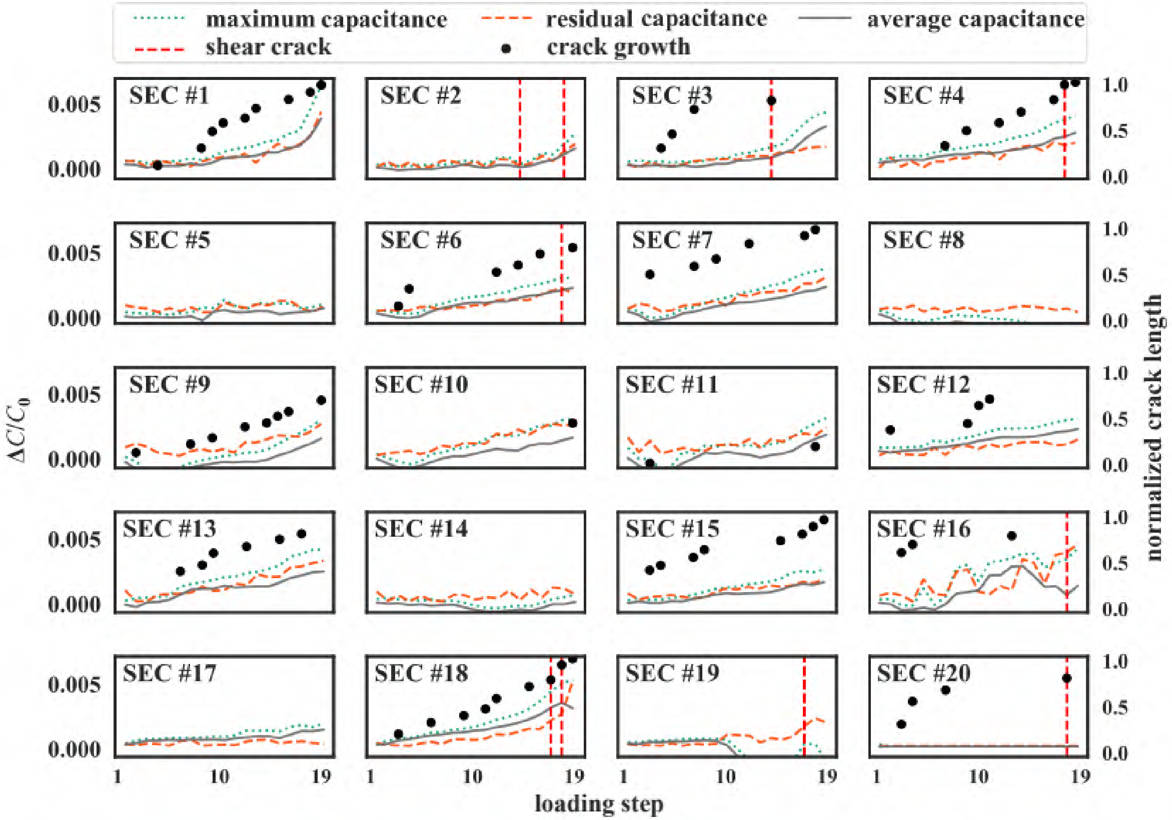
BACKGROUND

Concrete Crack Detection and Monitoring Using a Capacitive Dense Sensor Array





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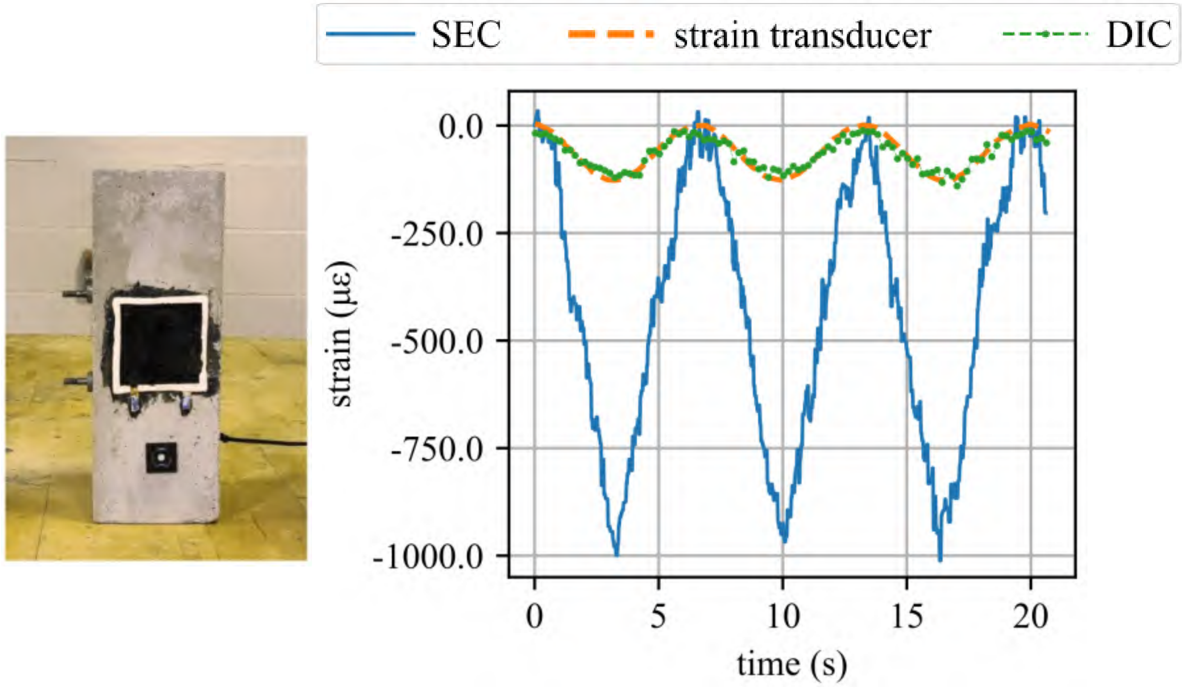
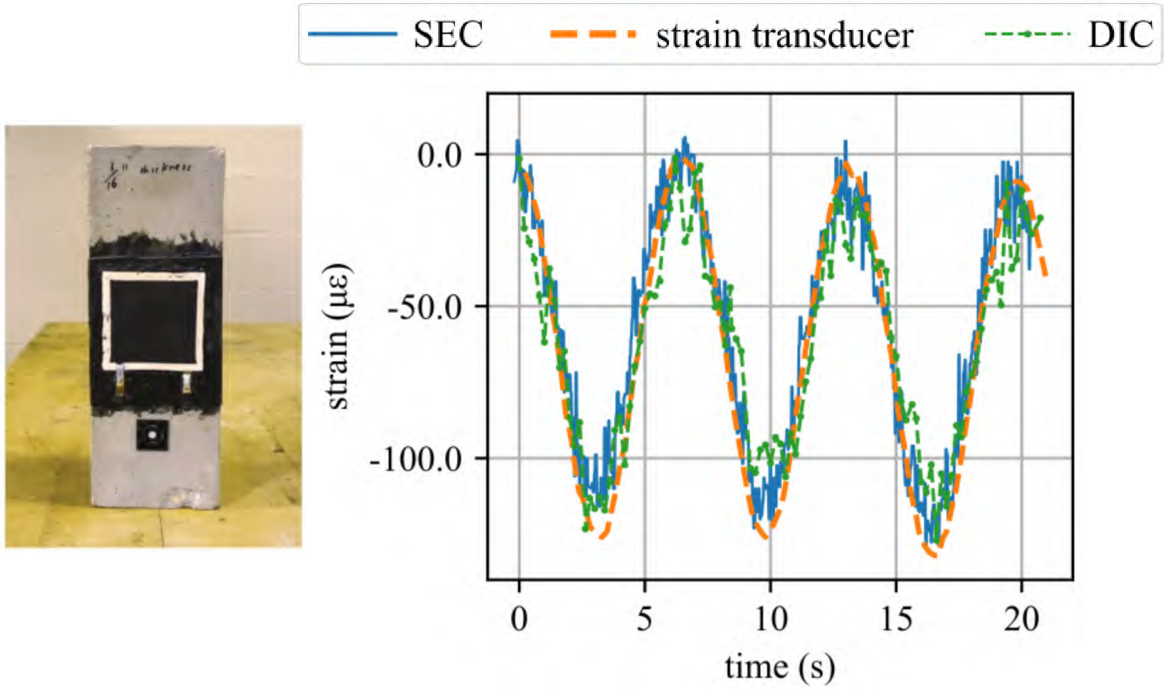
BACKGROUND

Investigation of electrically isolated capacitive sensing skins on concrete to reduce structure/sensor capacitive coupling





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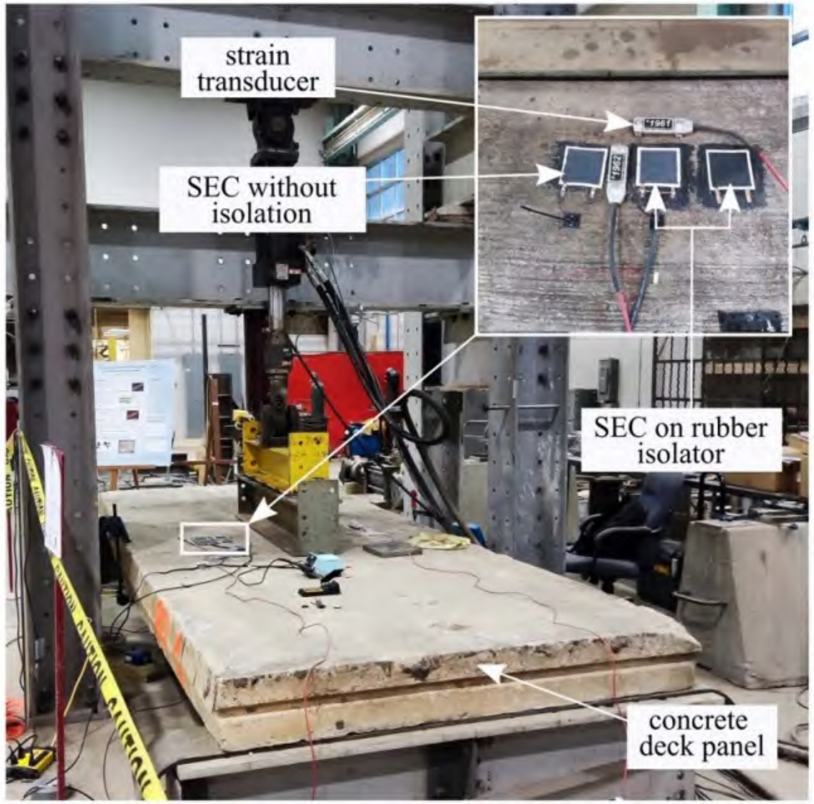

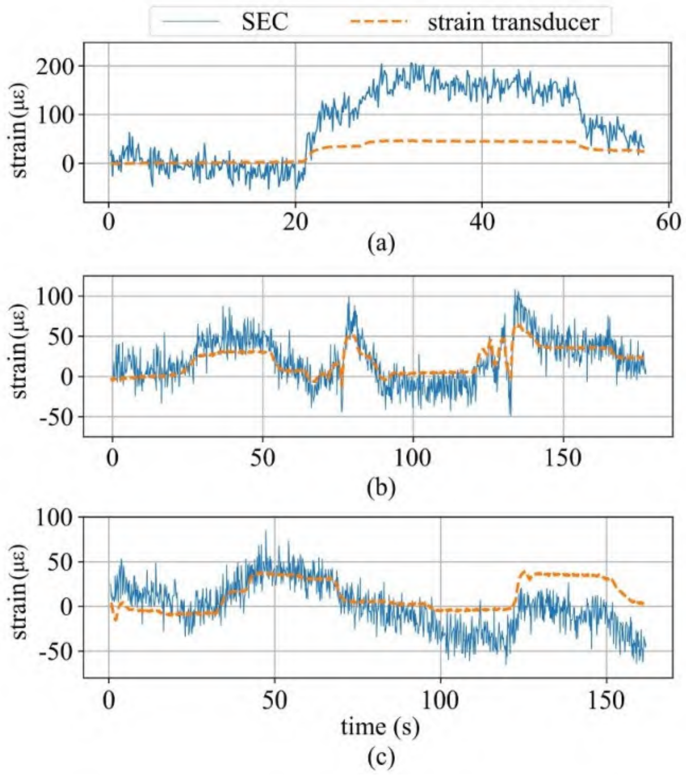

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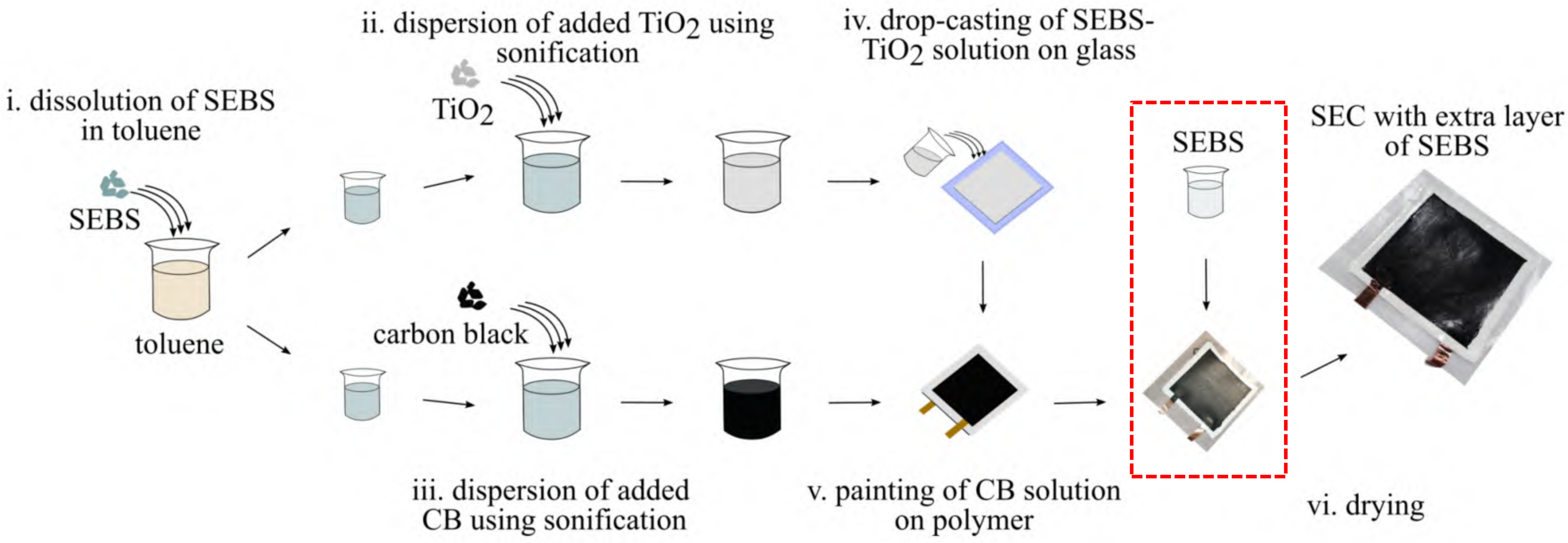
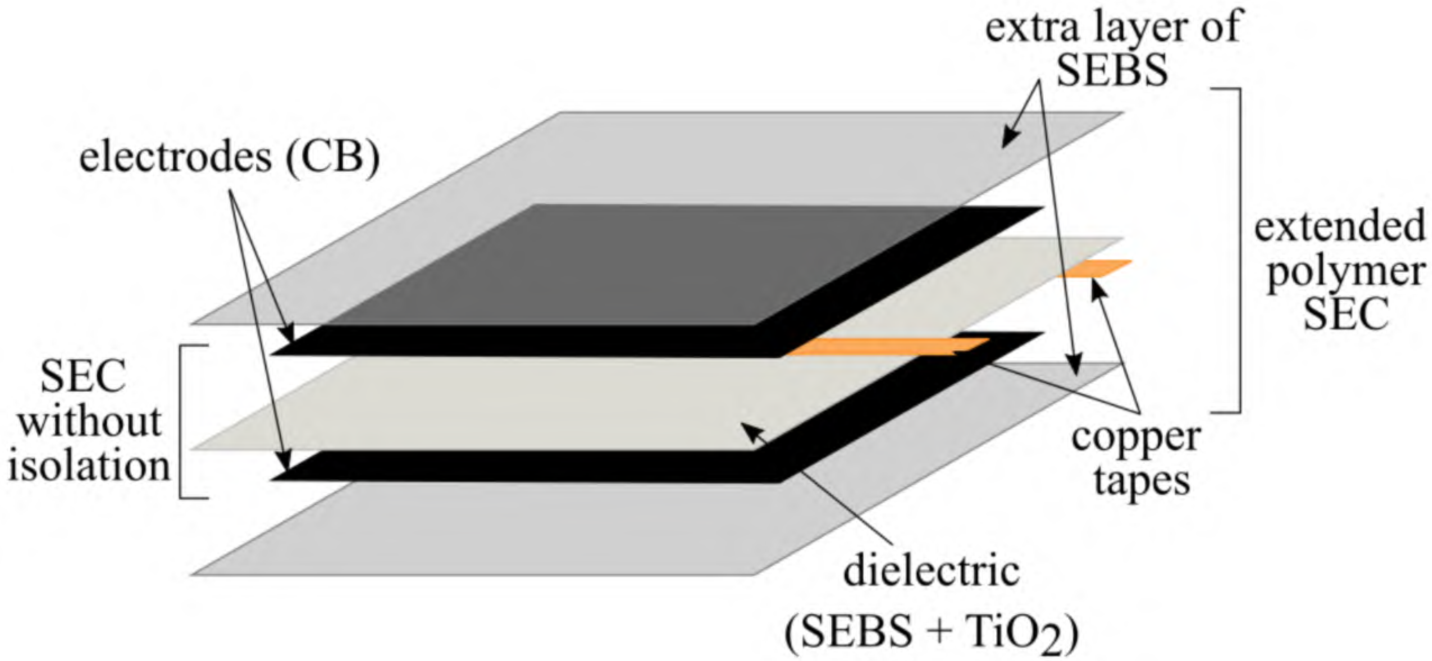
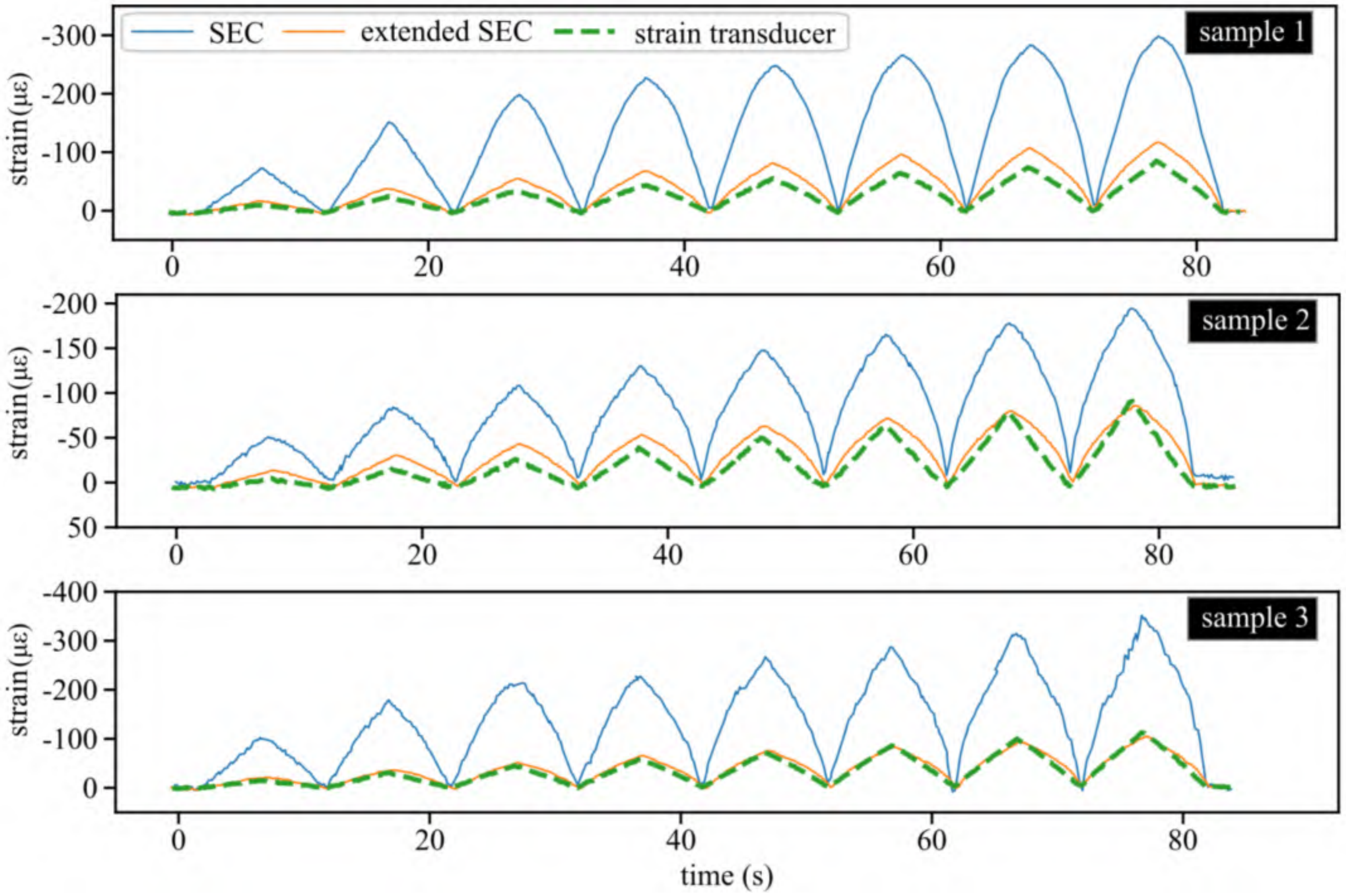
EXTENDED SEC



EXTENDED SEC



STRAIN DATA FROM EXPERIMENT



CONCRETE SURFACES WITH DIFFERENT FINISHING

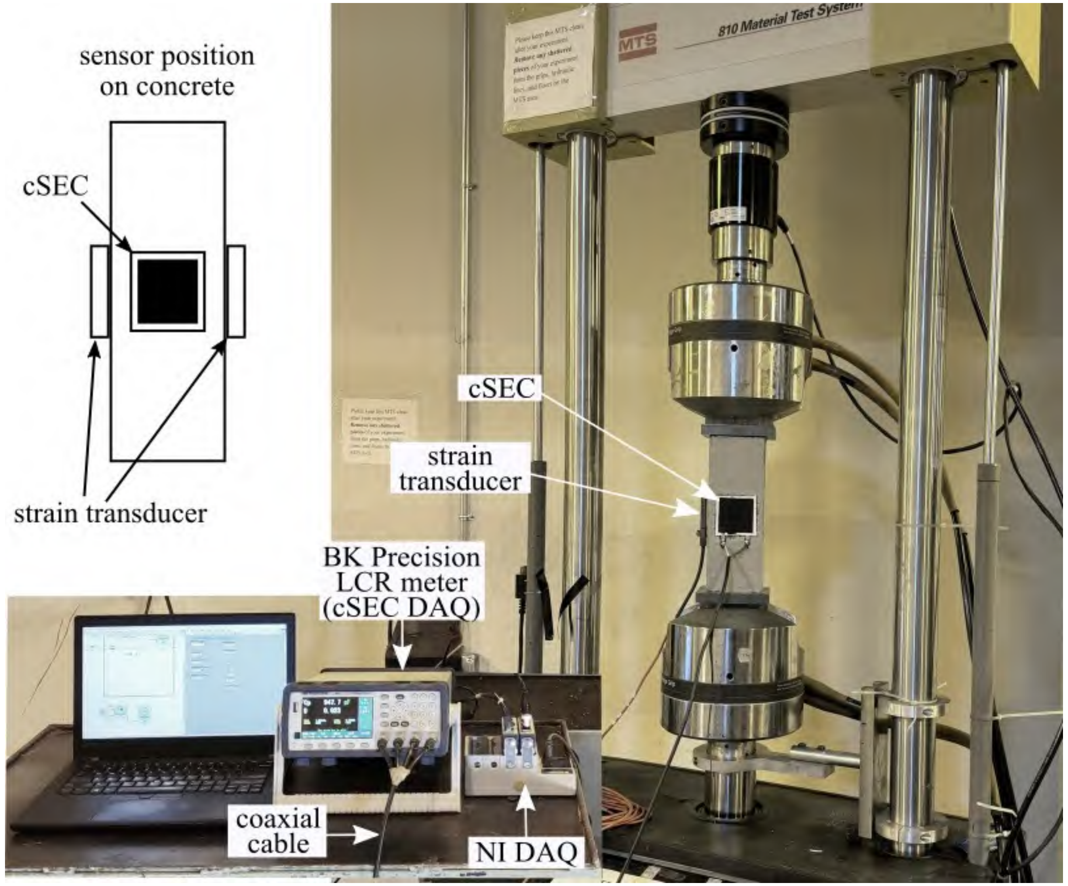
Smooth

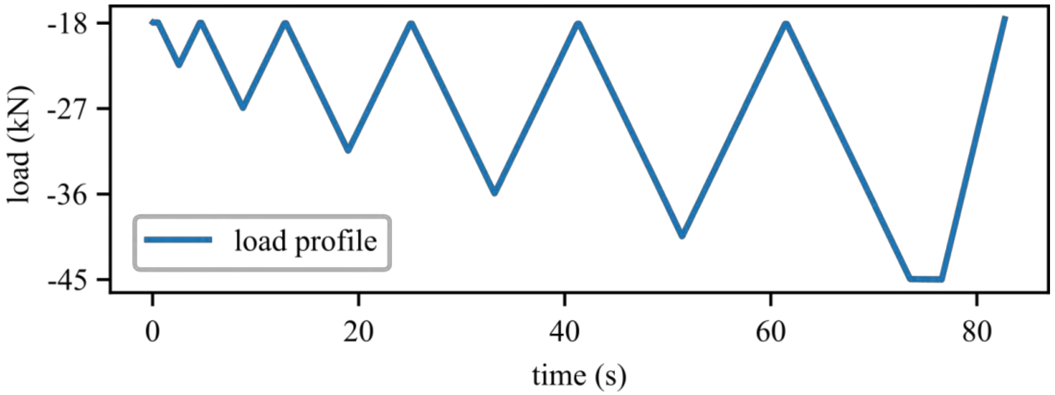
Rough

Dot grid

Vertical groove

MATERIAL, SET UP AND LOADING

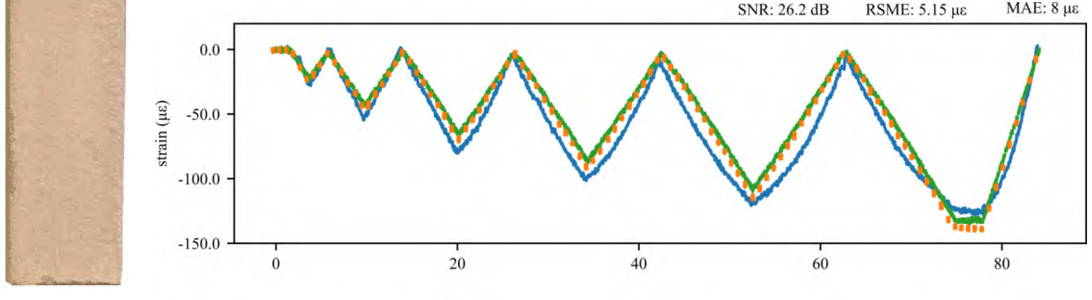




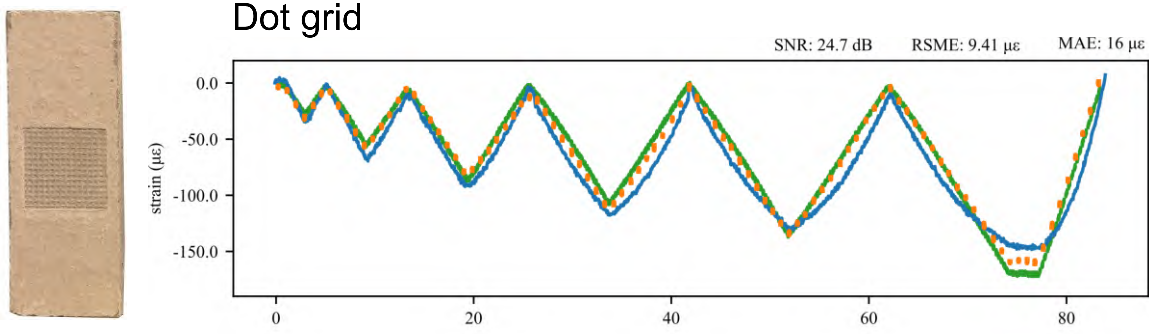
STRAIN DATA

cSEC — strain transducer 1 — strain transducer 2

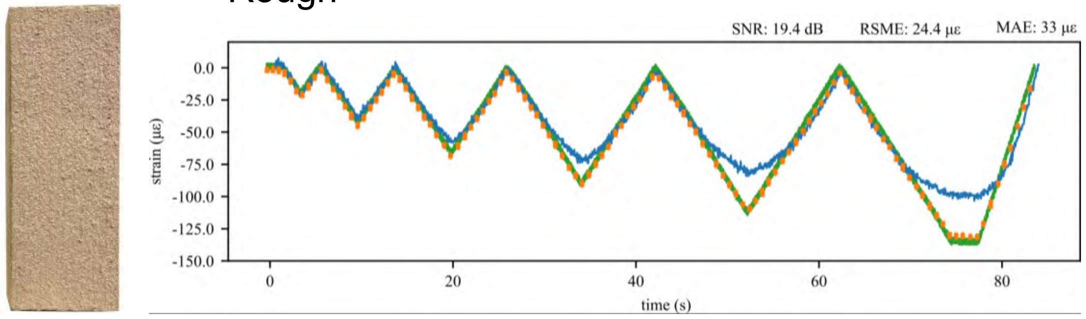
Smooth



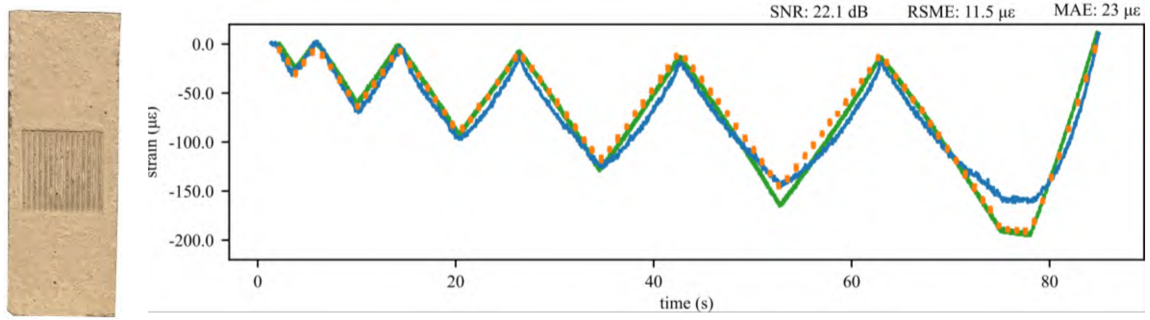
Dot grid



Rough



Vertical groove



RESULTS

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 $\mu\epsilon$

CONCLUSION

- 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 compared to other surfaces.

- The work demonstrated SEC's potential as a flexible and reliable option for structural health monitoring, capable of accurate strain measurement across various surface textures

ACKNOWLEDGEMENT

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