ELASTIC SENSING SKIN FOR MONITORING OF CONCRETE STRUCTURES

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Thesis defense

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University of South Carolina
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CONTENTS

PUBLICATIONS FROM THIS WORK

1. **Emmanuel Ogunniyi**, Alexander Vereen, Austin RJ Downey, Simon Laflamme, Jian Li, Caroline Bennett, William Collins, Hongki Jo, Alexander Henderson, and Paul Ziehl. Investigation of electrically isolated capacitive sensing skins on concrete to reduce structure/sensor capacitive coupling. *Measurement Science and Technology*, 34(5):055113, 2023.

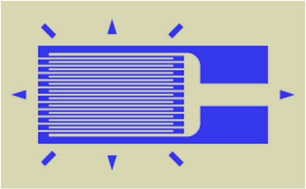
2. **Emmanuel Ogunniyi**, Han Liu, Austin RJ Downey, Simon Laflamme, Jian Li, Caroline Bennett, William Collins, Hongki Jo, and Paul Ziehl. Soft elastomeric capacitors with an extended polymer matrix for strain sensing on concrete. In *Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2023*, volume 12486, pages 262–270. SPIE, 2023.

3. **Emmanuel Ogunniyi**, Han Liu, Austin RJ Downey, Simon Laflamme, Jian Li, Caroline Bennett, William Collins, Hongki Jo, Alexander Henderson, and Paul Ziehl. Enhancing Structural Health Monitoring with direct coated Carbon Black on monitored surface for Elastomeric Capacitors adhesion (Not yet submitted)

INTRODUCTION

HEALTH MONITORING OF CIVIL STRUCTURES

- 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

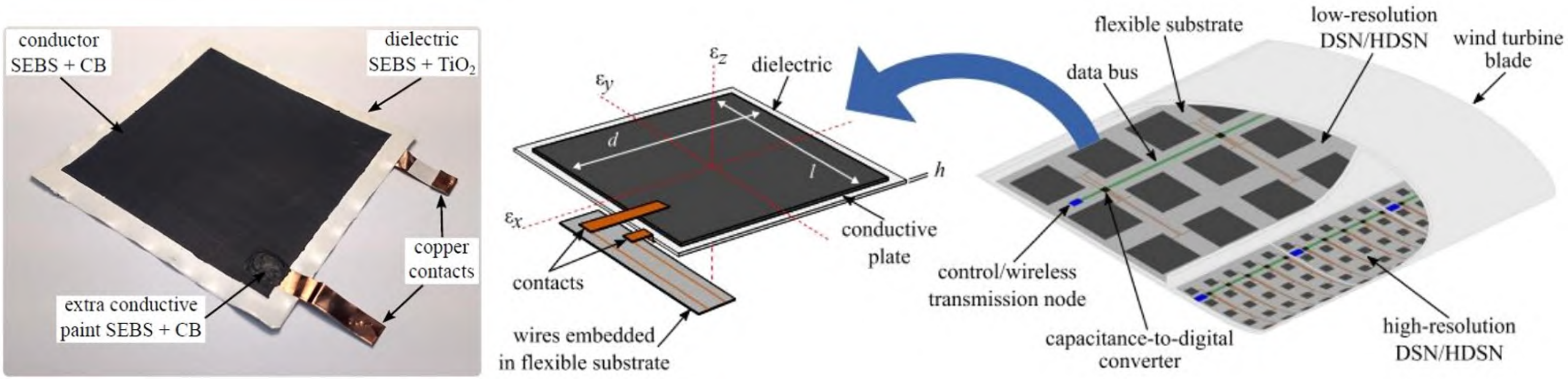


Resistive strain gauge

Fiber Bragg gratings

linear variable differential transformers

SOFT ELASTOMERIC SENSOR (SEC)

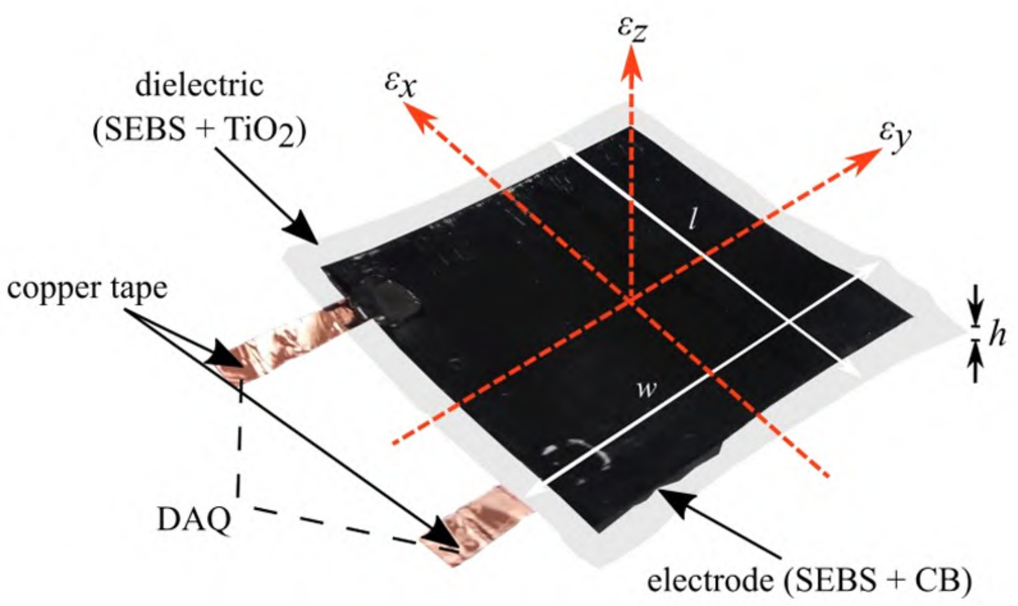


The sensor has the following features:

- 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
- Inherits the mechanical properties of an elastomer

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

$$C = \epsilon_0 \epsilon_\mathrm{r} \frac{lw}{h}$$

Parallel plate capacitor

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

Gradient w.r.t. deformation

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

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

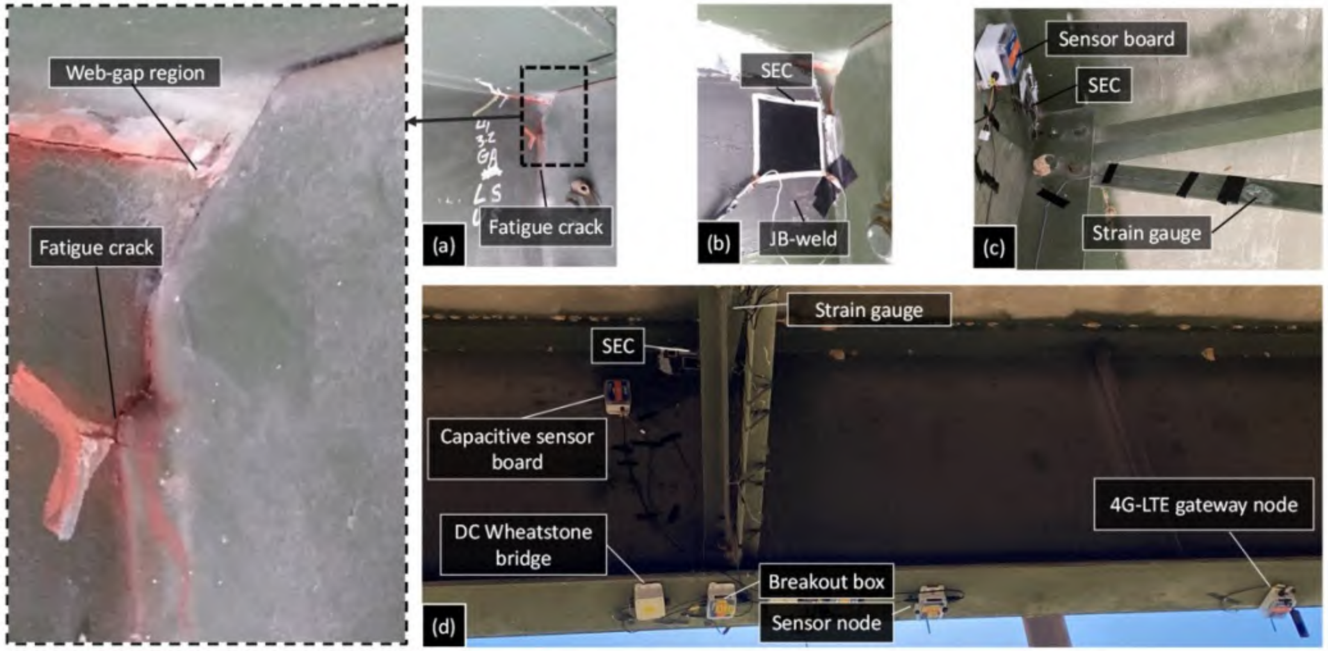
$$\frac{\Delta C}{C_0} = \frac{1}{1-\nu}(\varepsilon_{\mathrm{l}} + \varepsilon_{w})$$

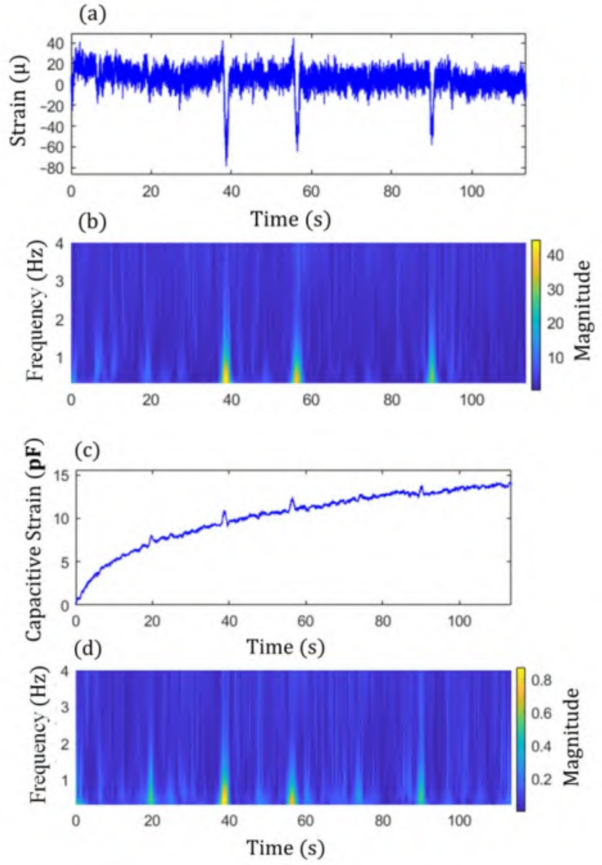
Capacitance in areal deformation

BACKGROUND

BACKGROUND

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

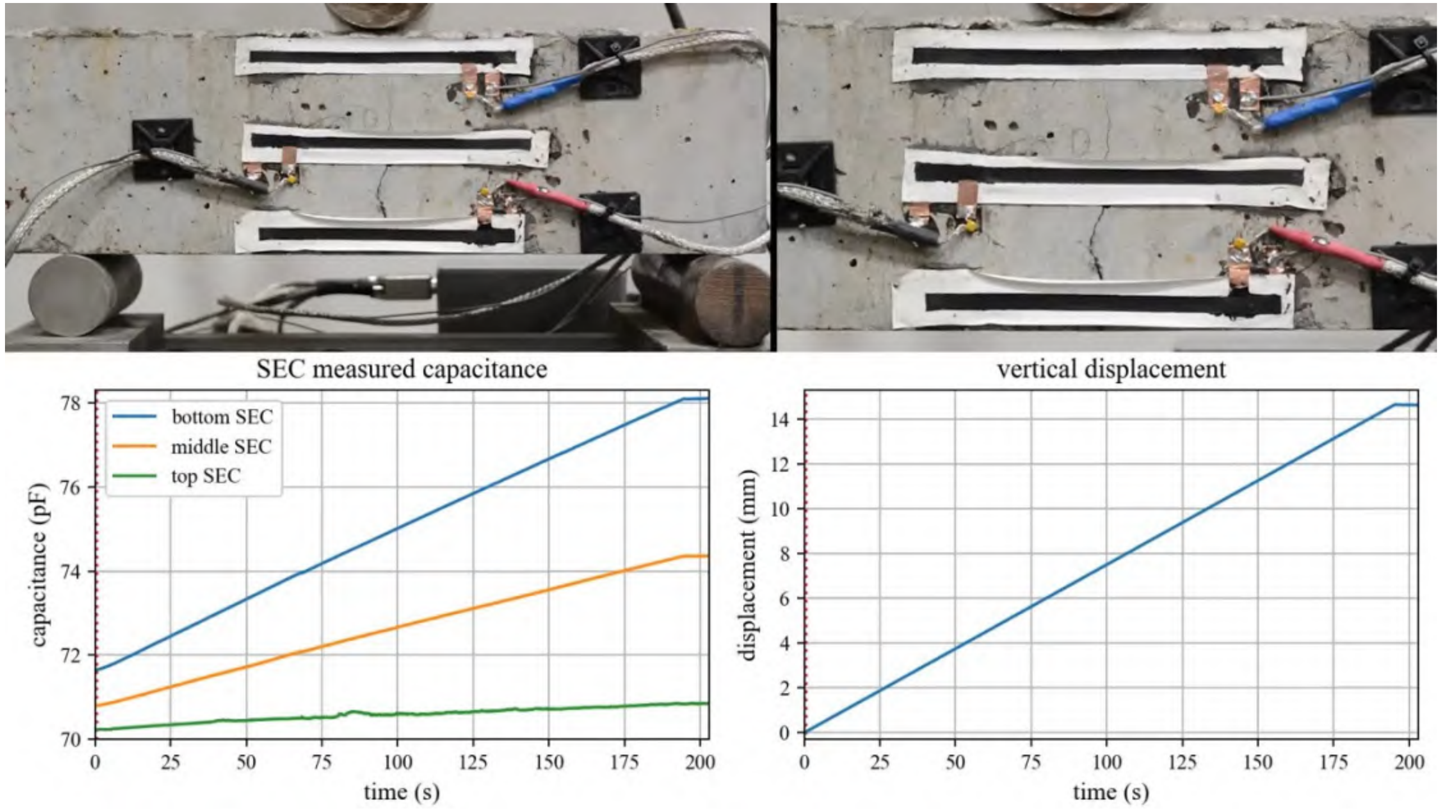




Taher, S. A., Li, J., Jeong, J.-H., Laflamme, S., Jo, H., Bennett, C., Collins, W. N., and Downey, A. R. J., "Structural health monitoring of fatigue cracks for steel bridges with wireless large-area strain sensors," Sensors **22**, 5076 (jul 2022)

BACKGROUND

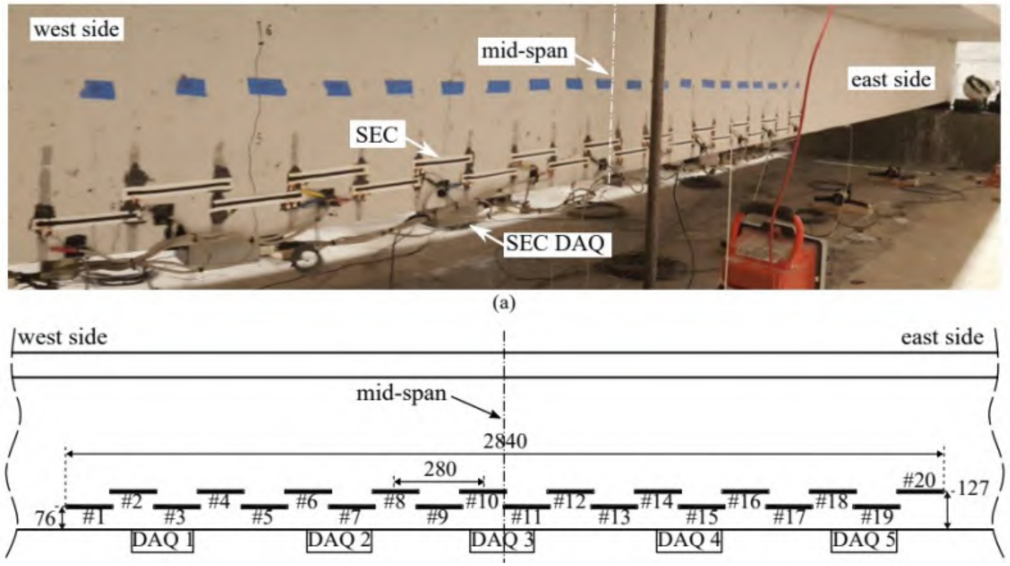
Concrete Crack Detection and Monitoring Using a Capacitive Dense Sensor Array

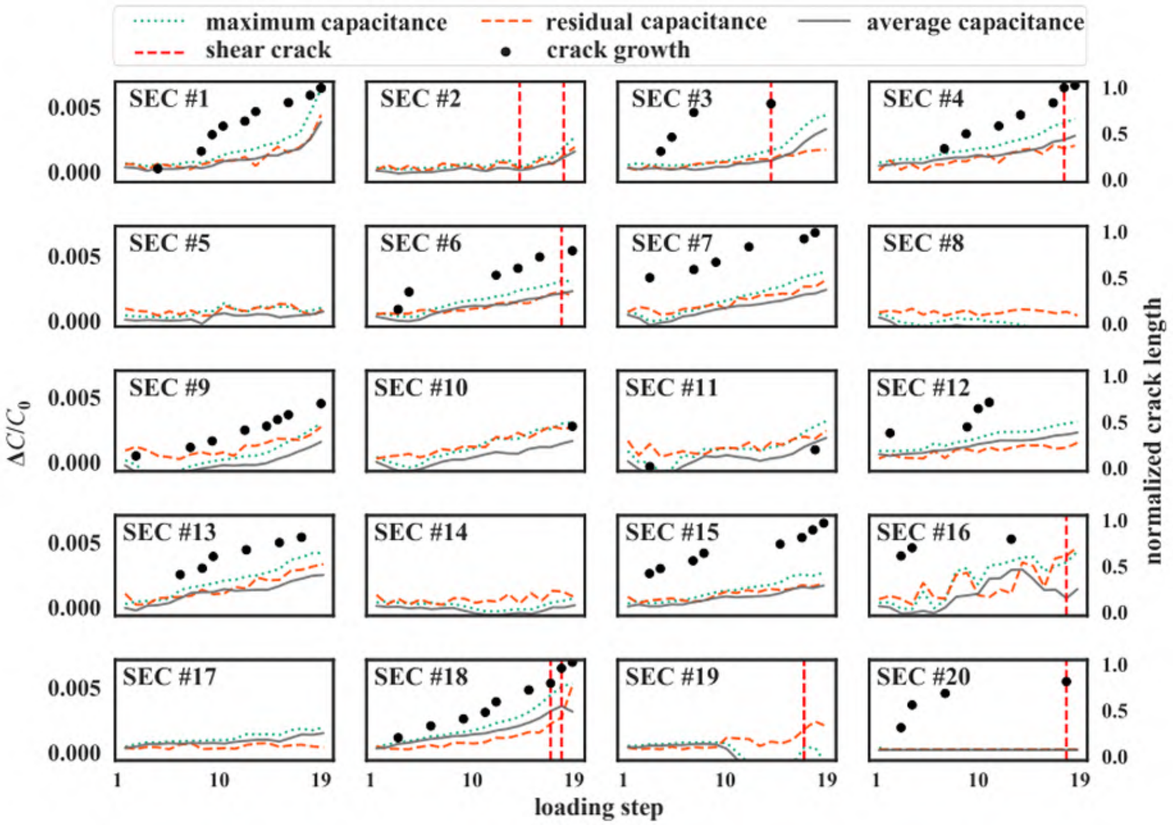


Yan, Jin, et al. "Concrete crack detection and monitoring using a capacitive dense sensor array." Sensors 19.8 (2019): 1843.

BACKGROUND

Concrete Crack Detection and Monitoring Using a Capacitive Dense Sensor Array

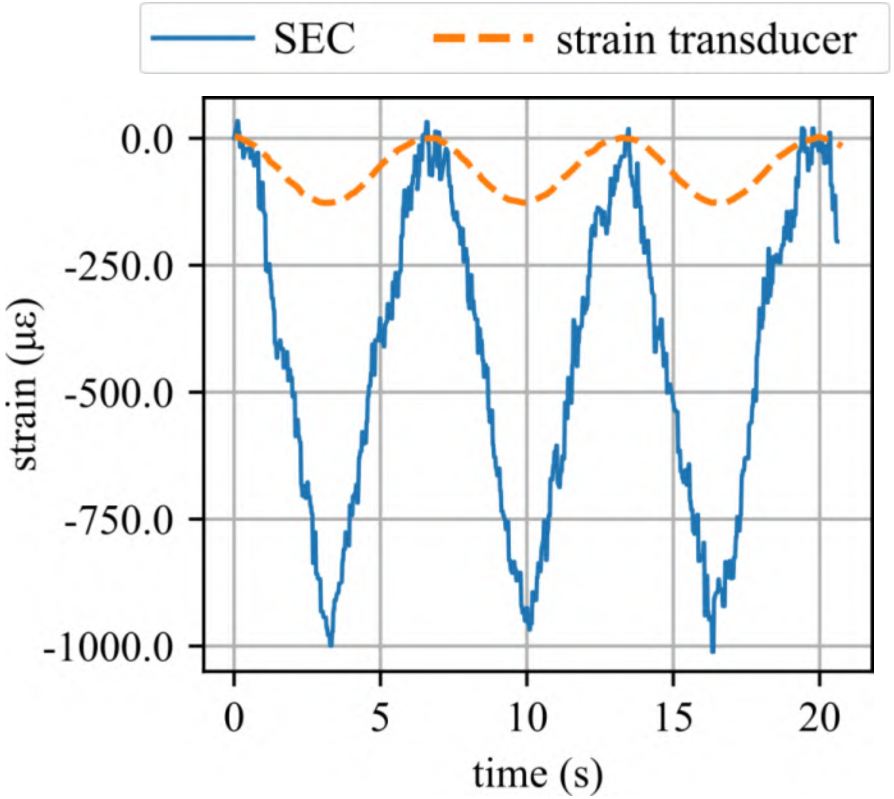




Yan, Jin, et al. "Concrete crack detection and monitoring using a capacitive dense sensor array." Sensors 19.8 (2019): 1843.

BACKGROUND: Challenge in concrete monitoring

- SEC/Concrete capacitance coupling causing signal amplification even after electrical grounding



INVESTIGATION 1

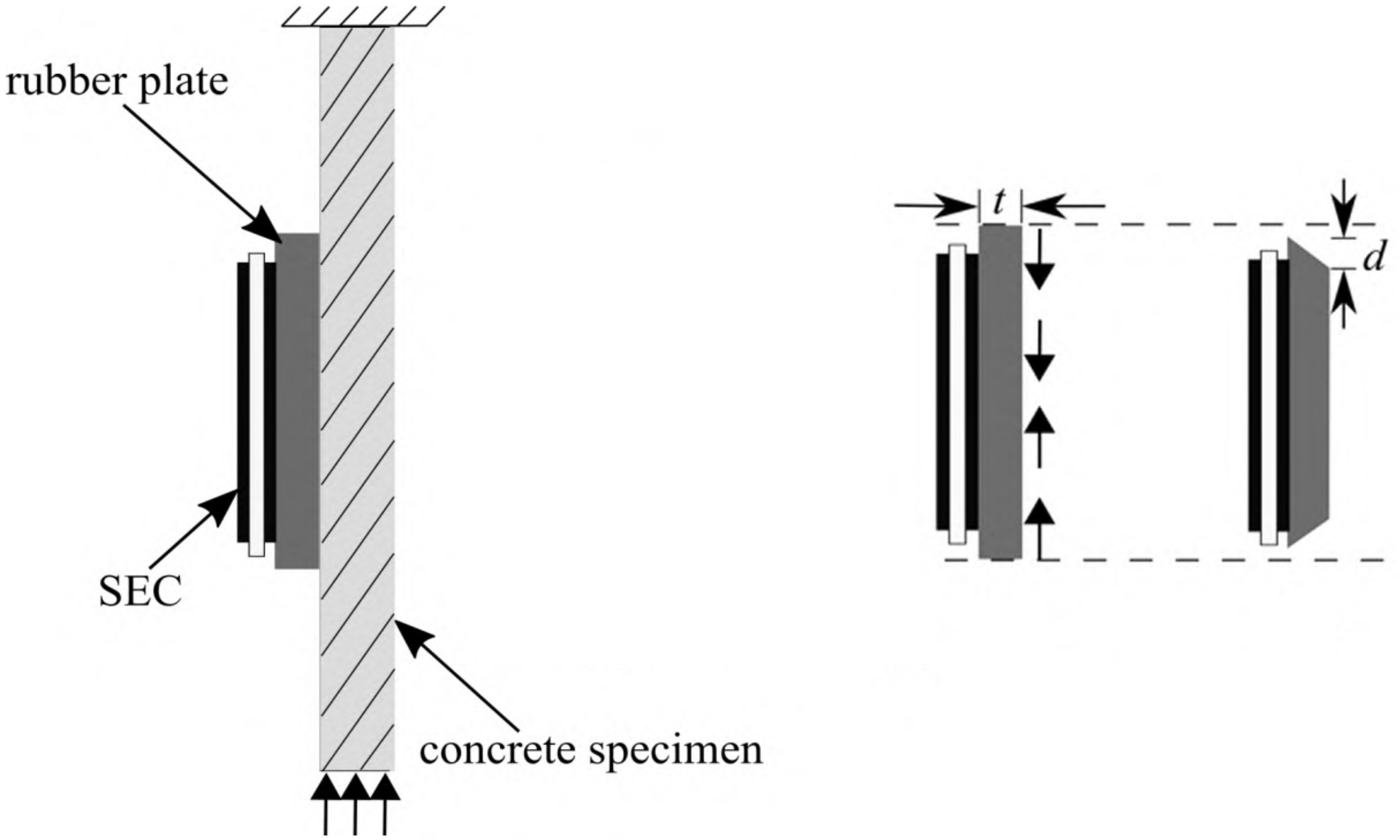
Reducing SEC/Concrete capacitance coupling via isolation

- Two rubber isolators (Natural rubber and Neoprene) were selected because their Poisson ratios are close to 0.5, similar to SEC's Poisson ratio.

Table 1. Table showing rubber properties for natural rubber and neoprene.

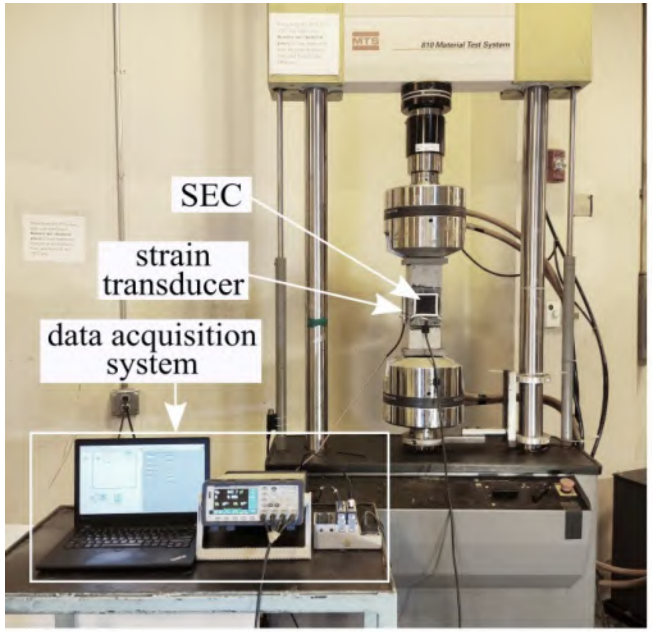
Properties	Natural rubber	Neoprene
Durometer or hardness range	40 A	40 A
Poisson's ratio	0.48–0.5	0.46–0.49
Tensile strength range	($\geq$ 17237 kN m^{-2})	5516–9653 kN m^{-2}
Elongation (range %)	300–900%	100–800%
Temperature range	93.3–200 °C	−34.4–121.1 °C

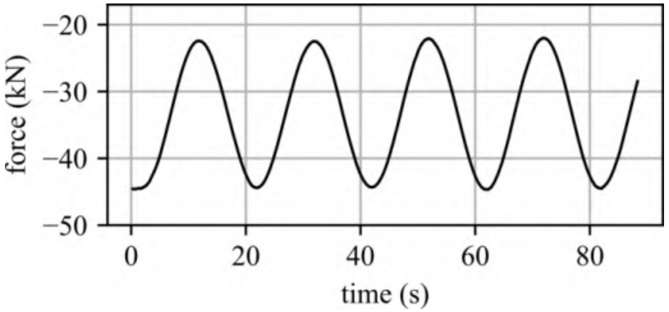
Isolation Principle



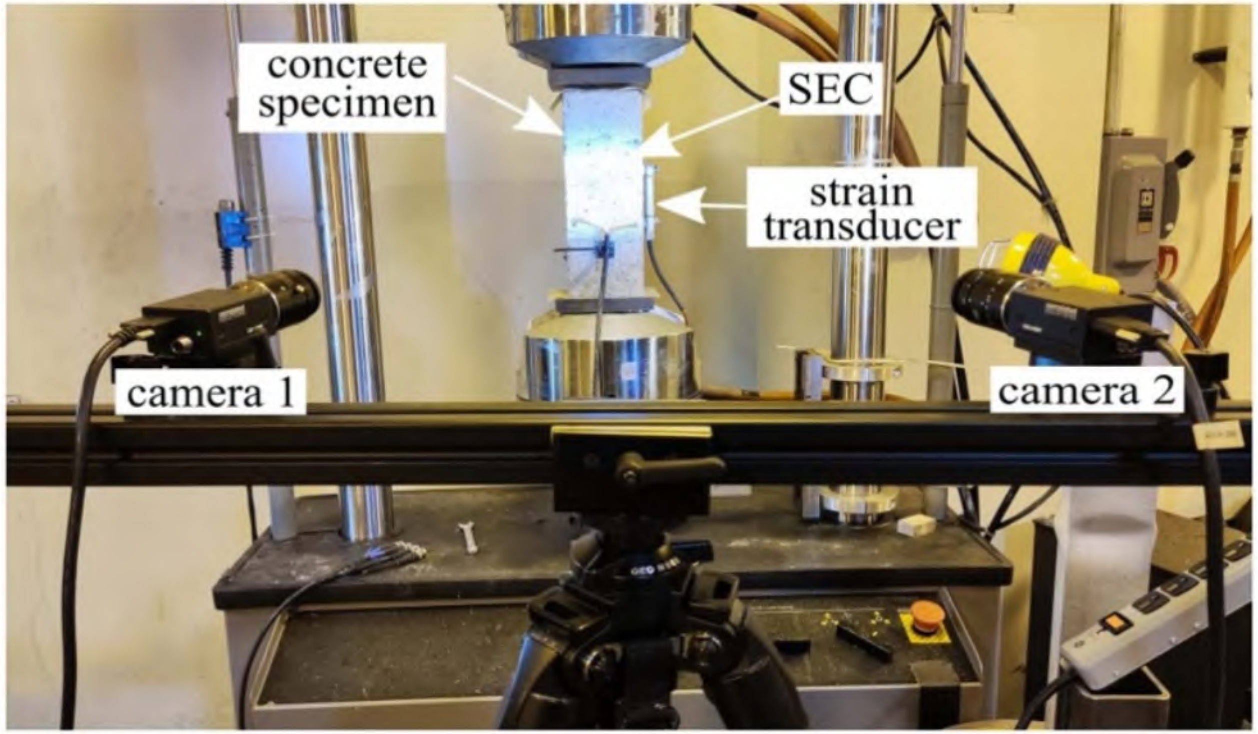
Rubber, SEC and concrete schematic

Experimental setup and loading

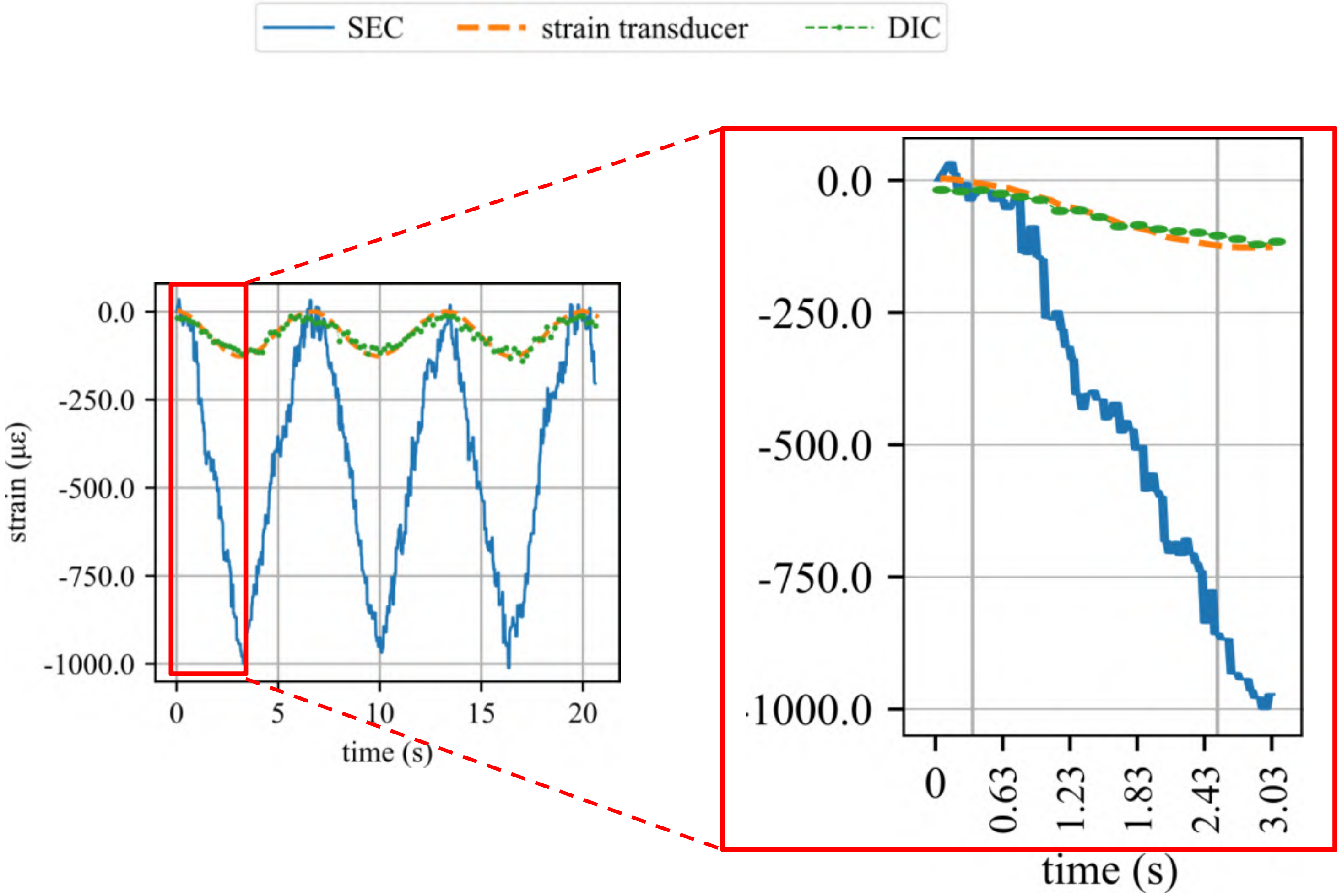


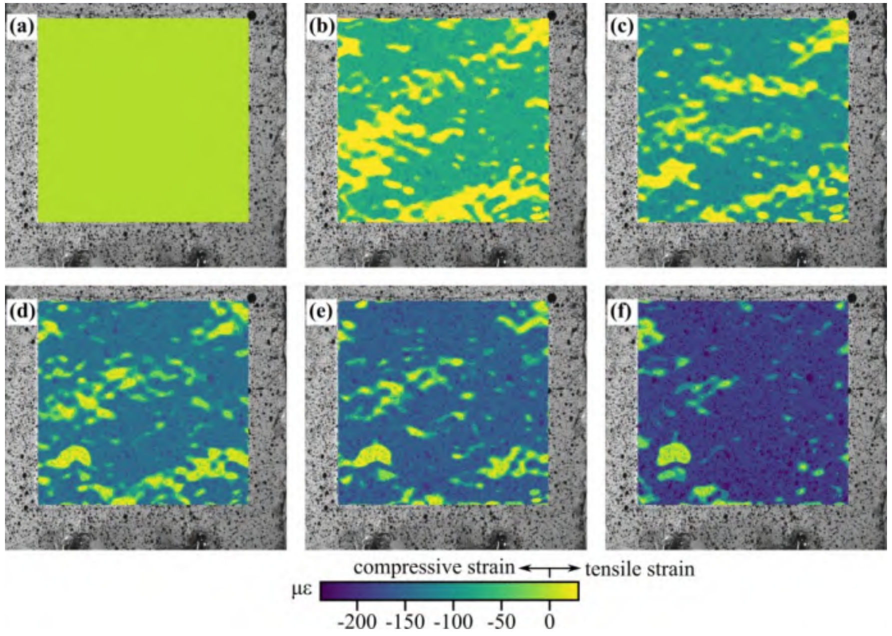


DIC setup



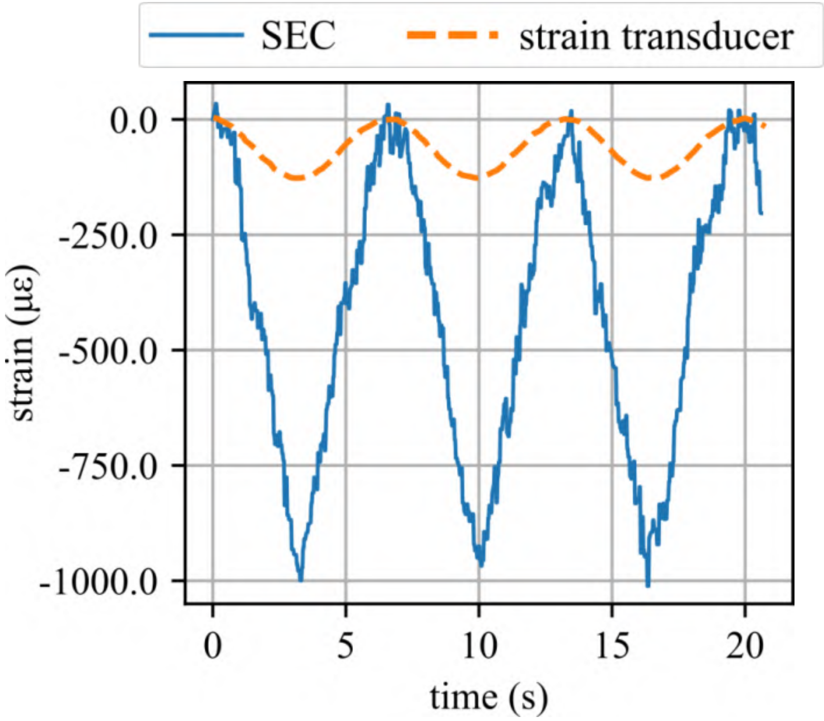
DIC strain investigation

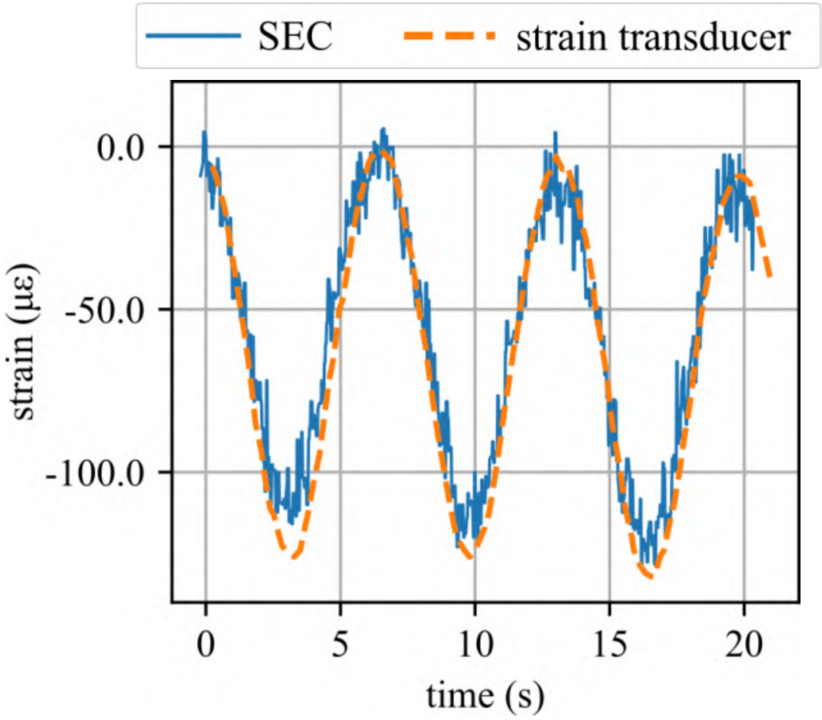




time (s)	SEC ($\mu\varepsilon$)	strain transducer ($\mu\varepsilon$)	DIC ($\mu\varepsilon$)
0	0	0	0
0.63	−37.6	−17.9	−25.4
1.23	−247.6	−52.8	−57.7
1.83	−421.1	−86.9	−87.1
2.43	−684.2	−115.2	−96.6
3.03	−1004	−126.9	−110.1

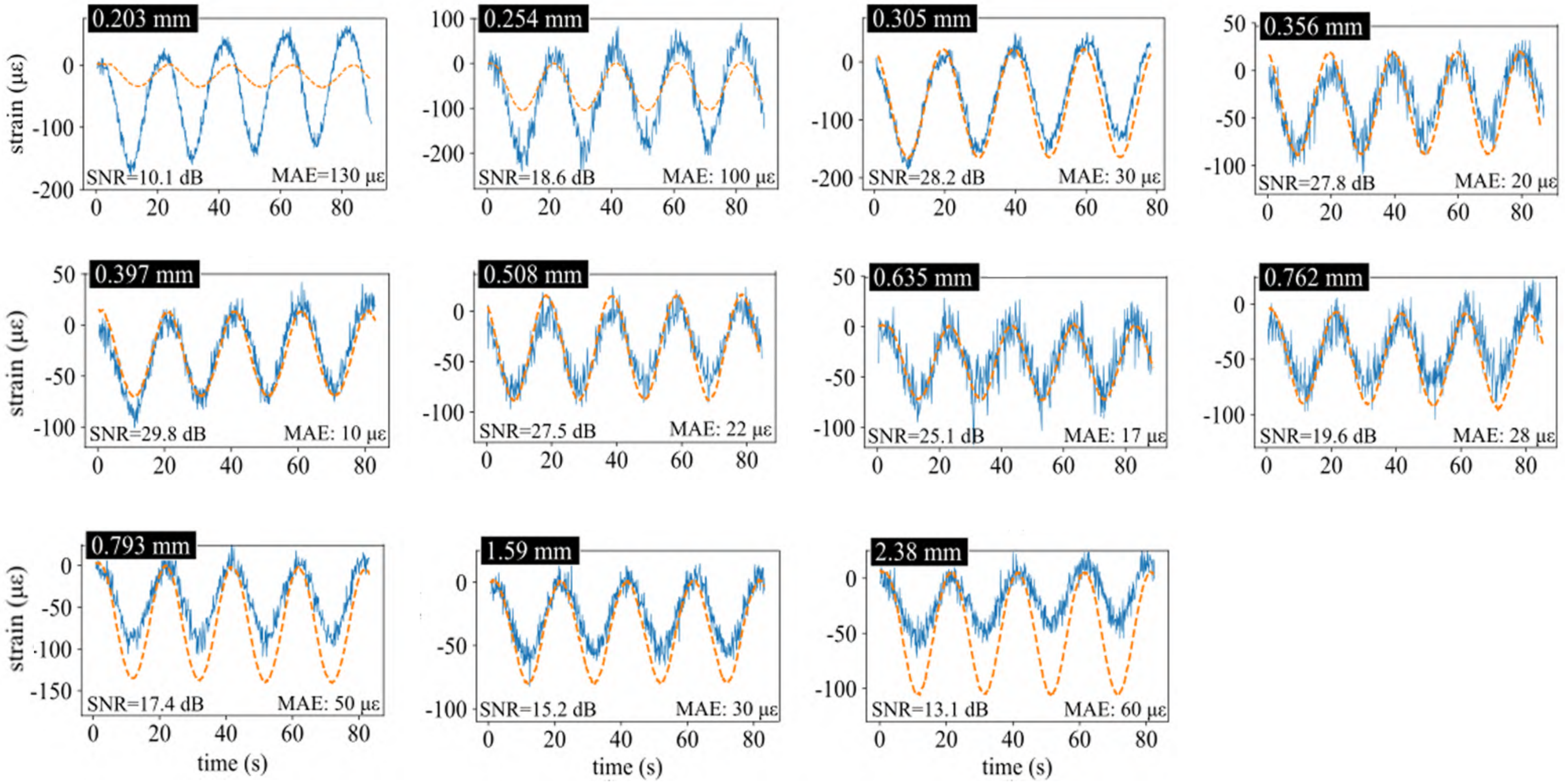
Initial result



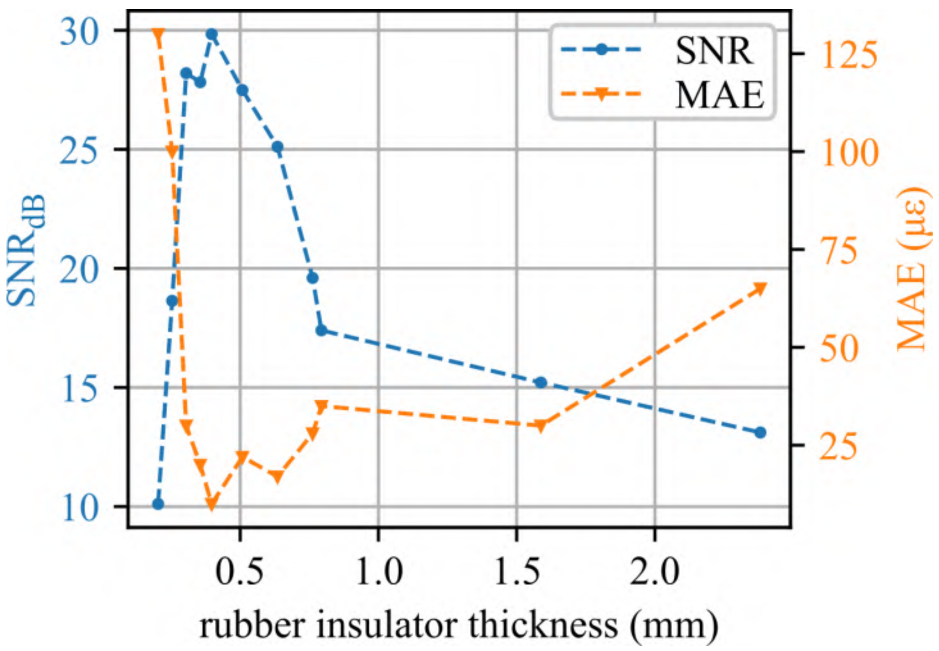


Ogunniyi, Emmanuel, et al. "Investigation of electrically isolated capacitive sensing skins on concrete to reduce structure/sensor capacitive coupling." Measurement Science and Technology (2023).

Isolation Thickness

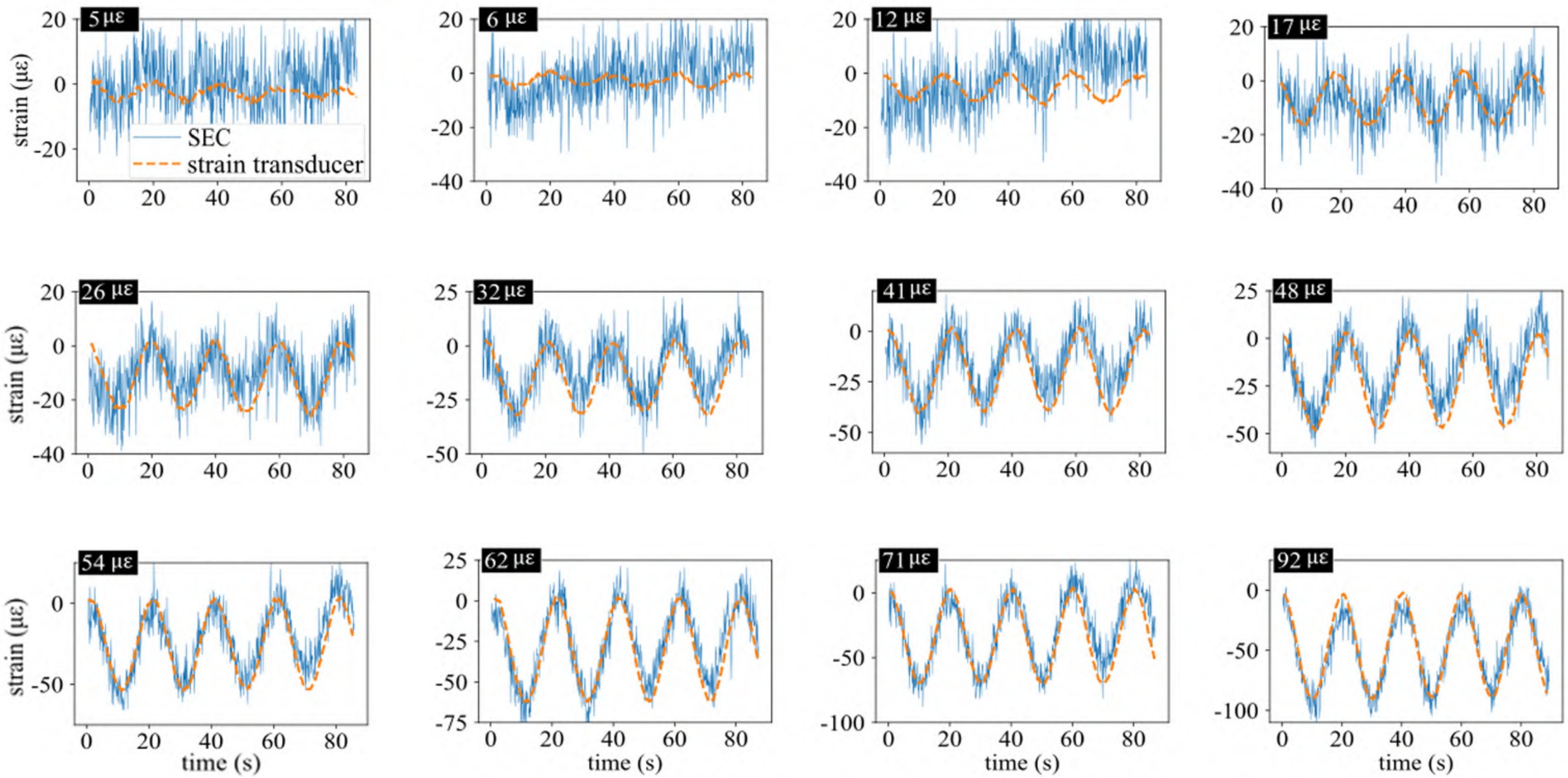


Performance metric

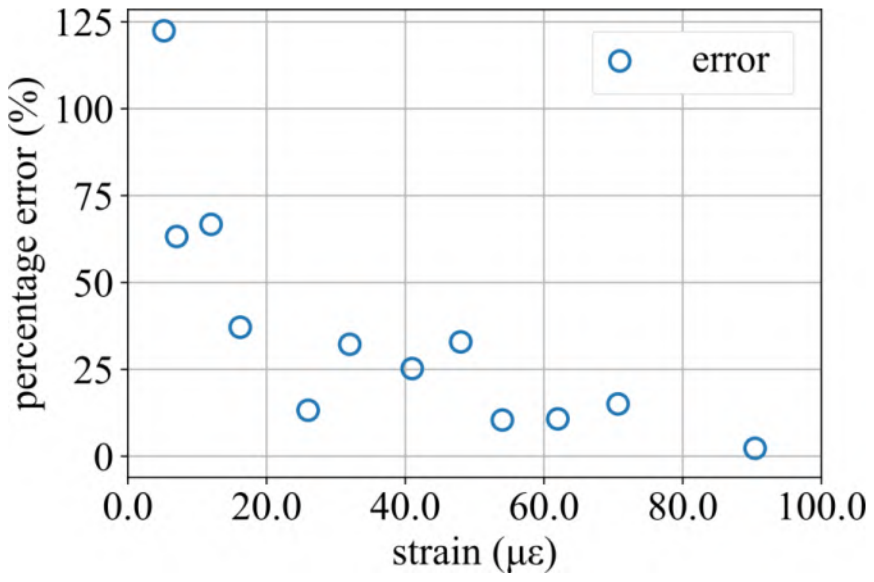


Highest SNR and lowest MAE at 0.397 mm

Strain range

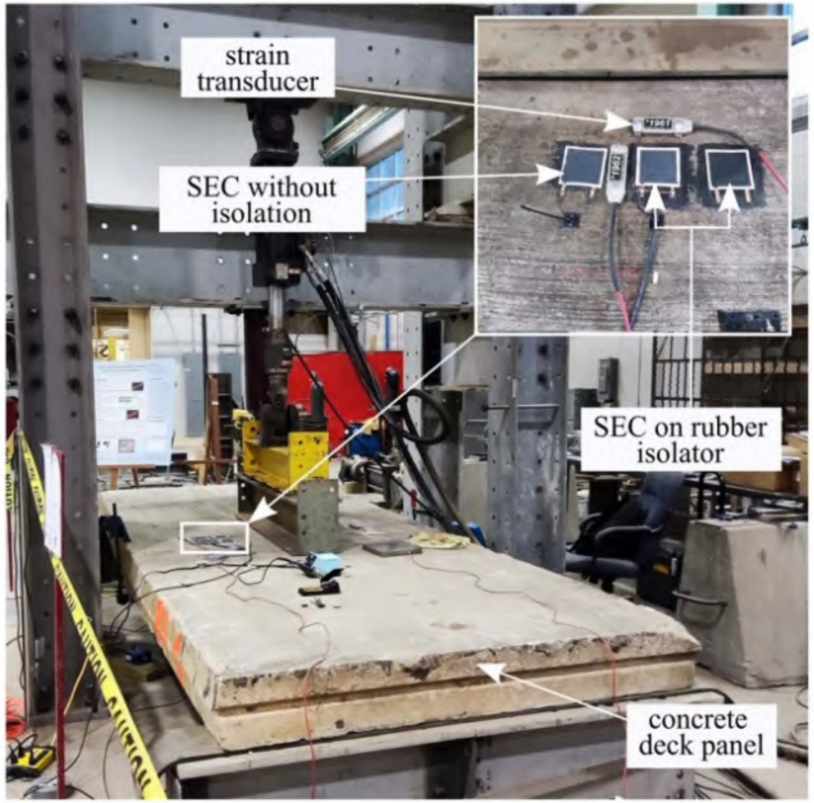


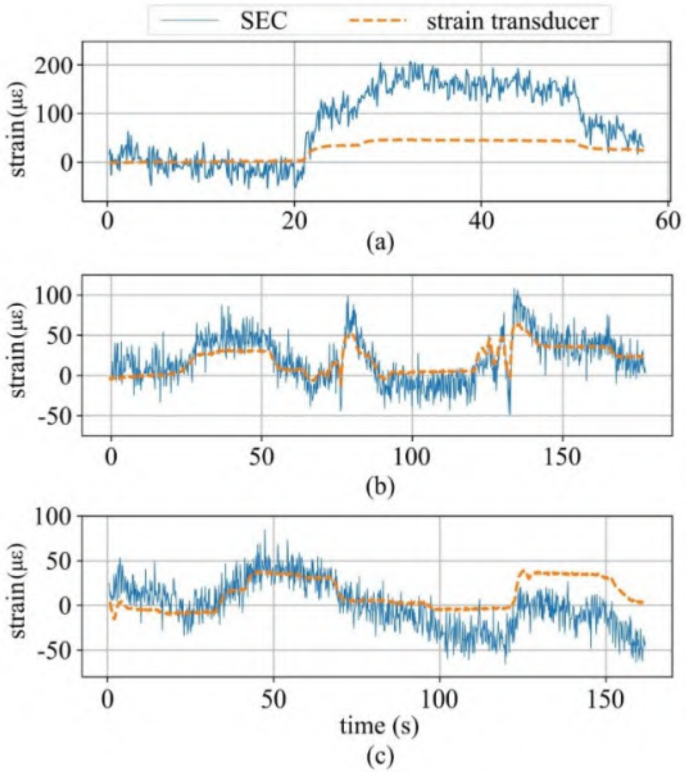
Performance metric



Data shows SEC is more suitable for monitoring strain above 25 microstrain on concrete structures

Bridge deck test





Rubber thickness

No isolation

0.397 mm

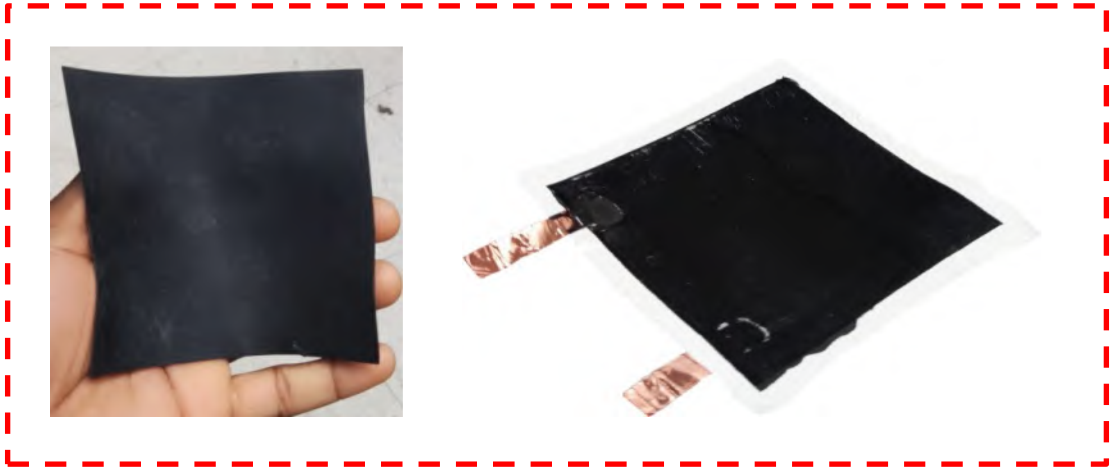
0.794 mm

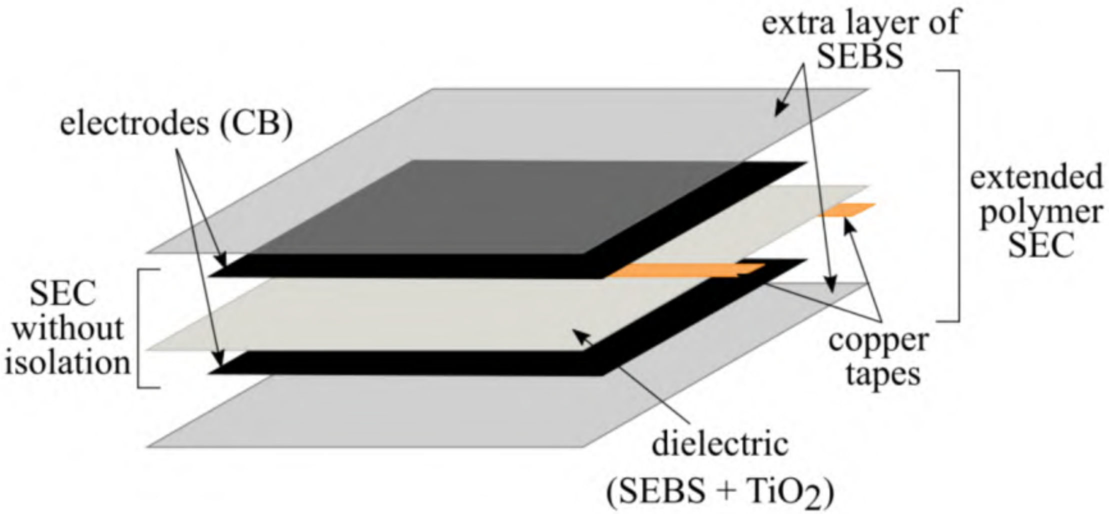
Ogunniyi, Emmanuel, et al. "Investigation of electrically isolated capacitive sensing skins on concrete to reduce structure/sensor capacitive coupling." Measurement Science and Technology (2023).

INVESTIGATION 2

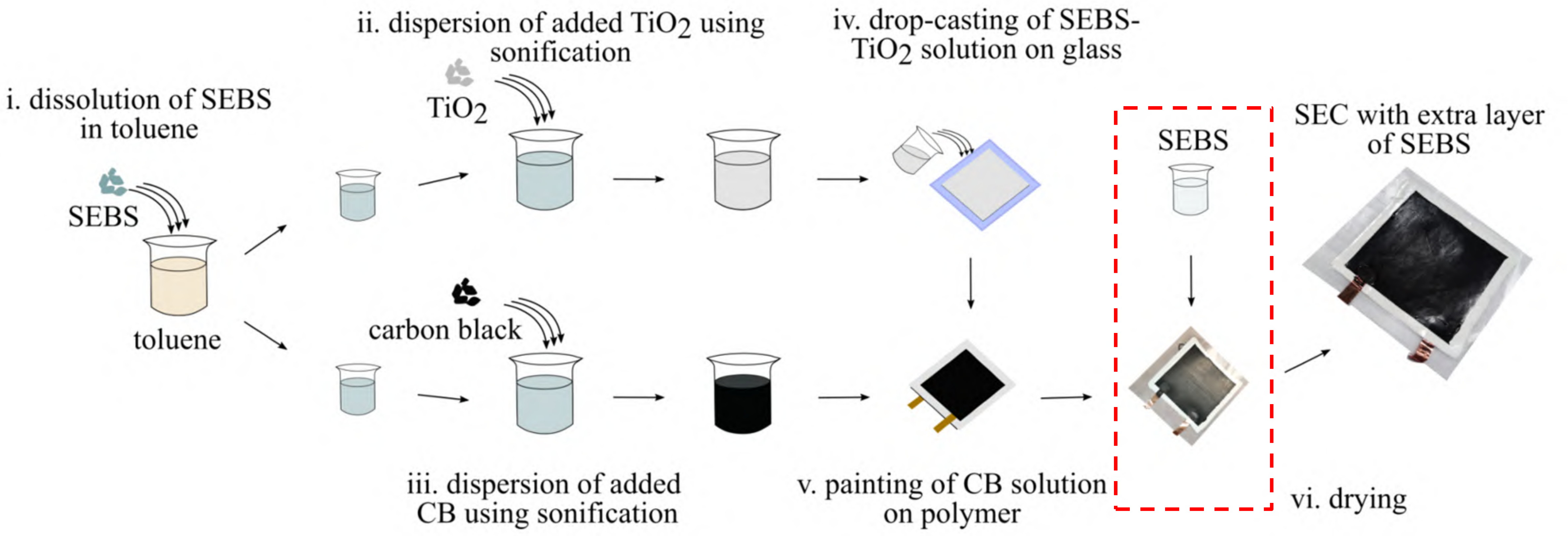
Why and How

SEC modification to achieve a robust and compact sensor

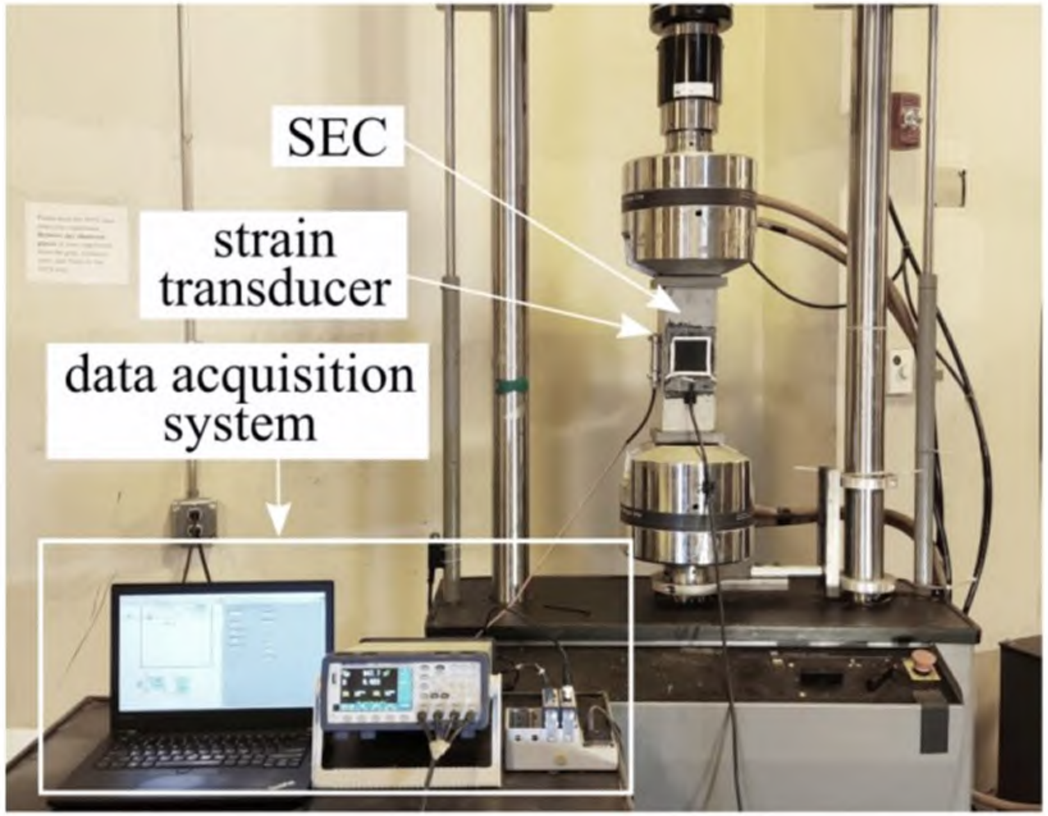


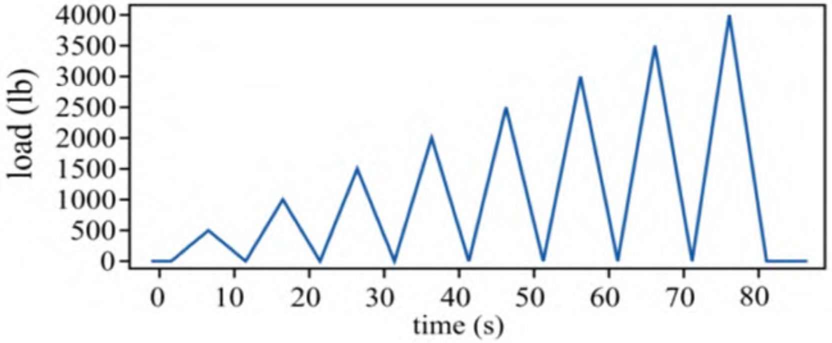


Fabrication Procedure : Extended SEC

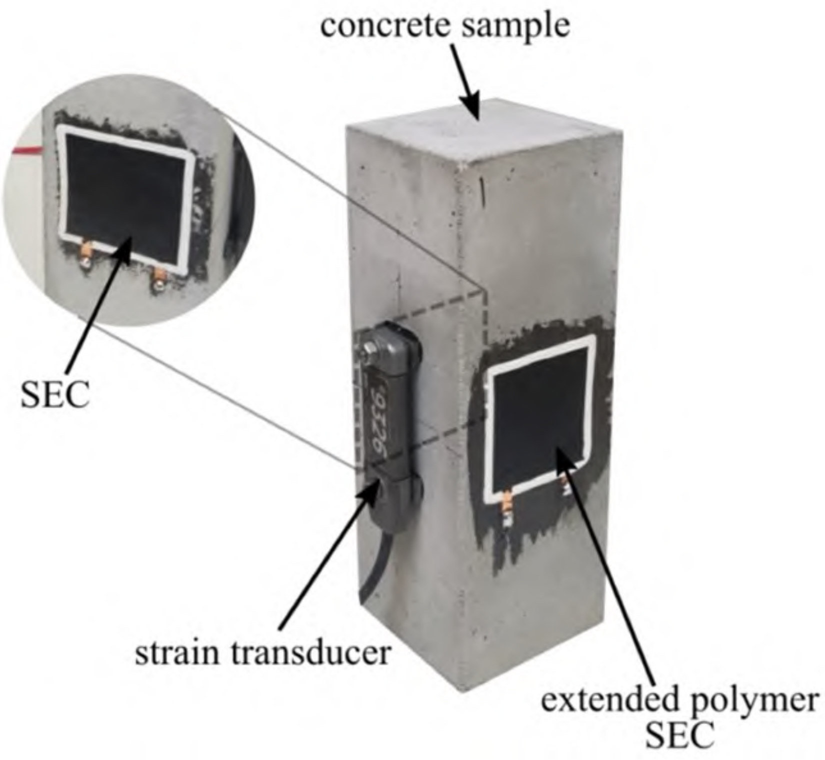


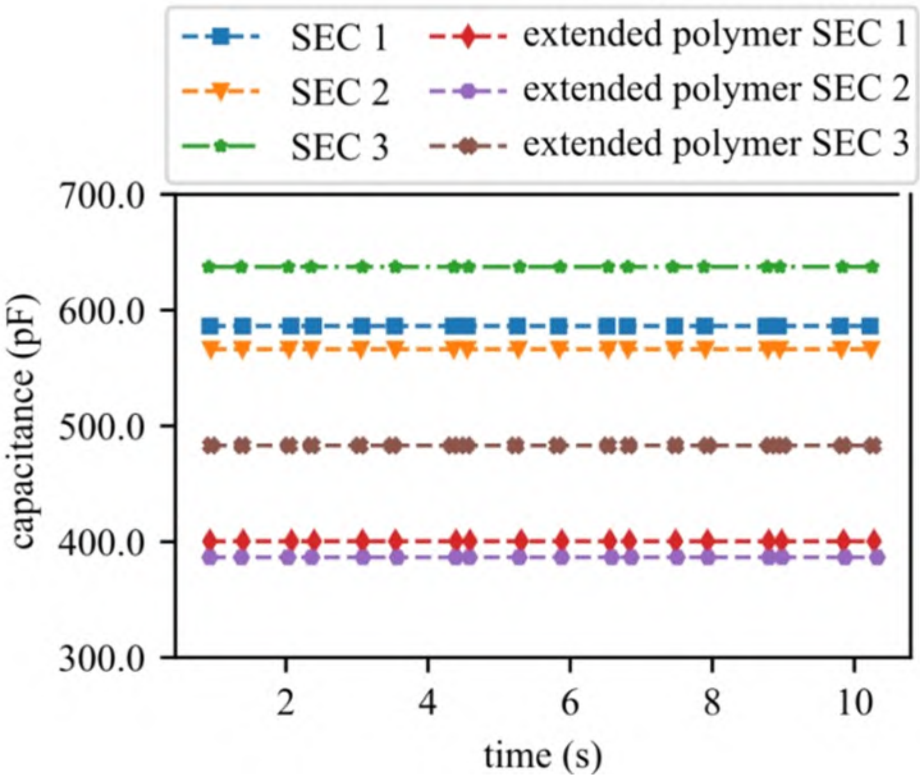
Material, Setup and Loading





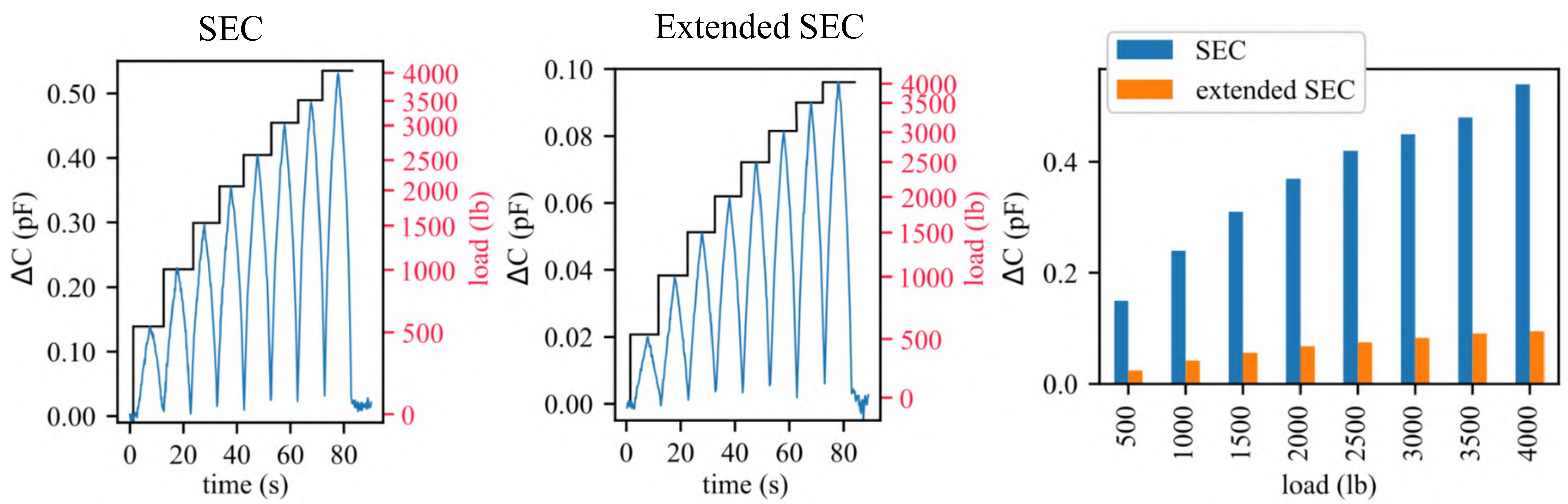
Nominal Capacitance



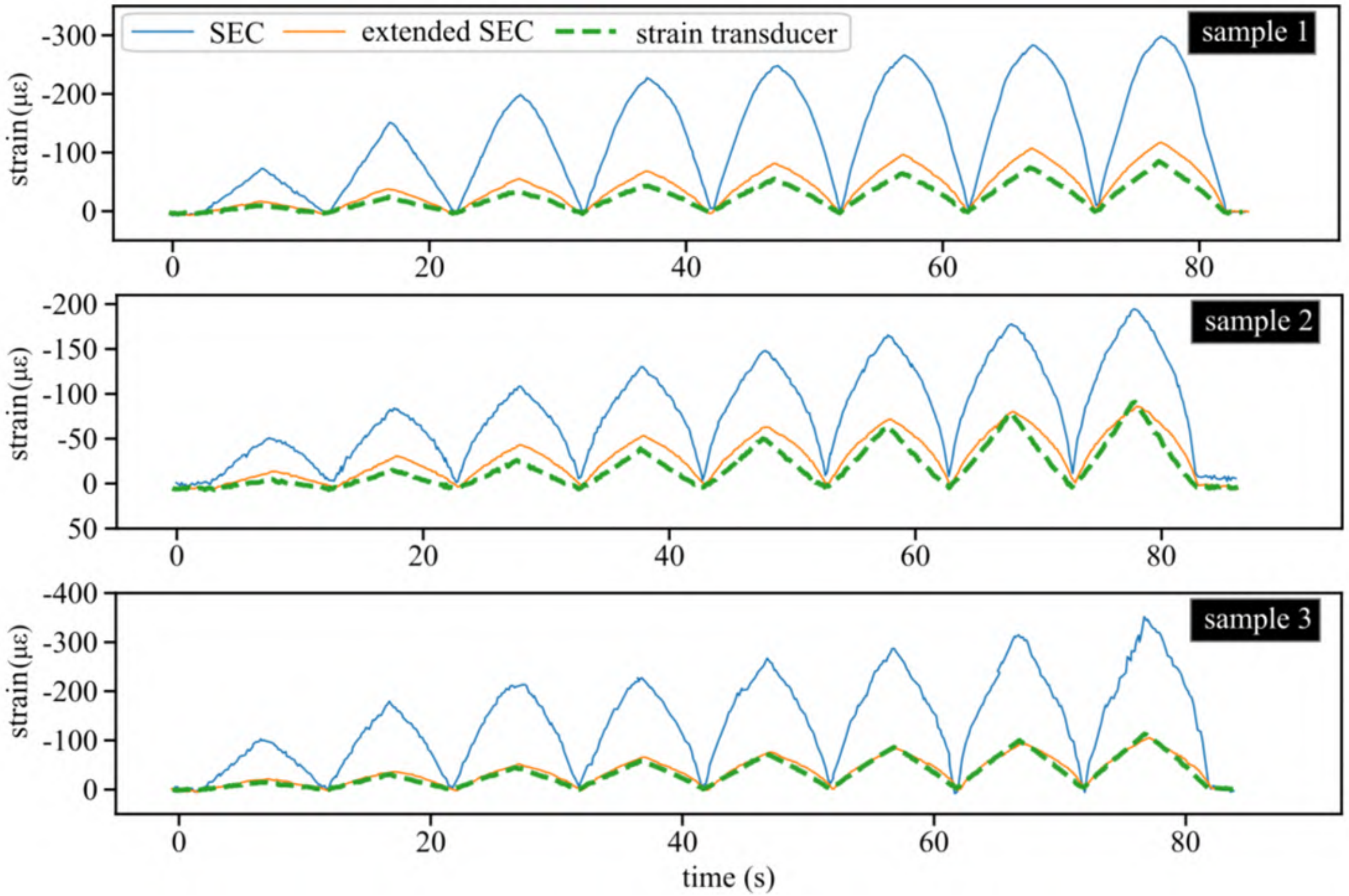


- Lower nominal capacitance achieved

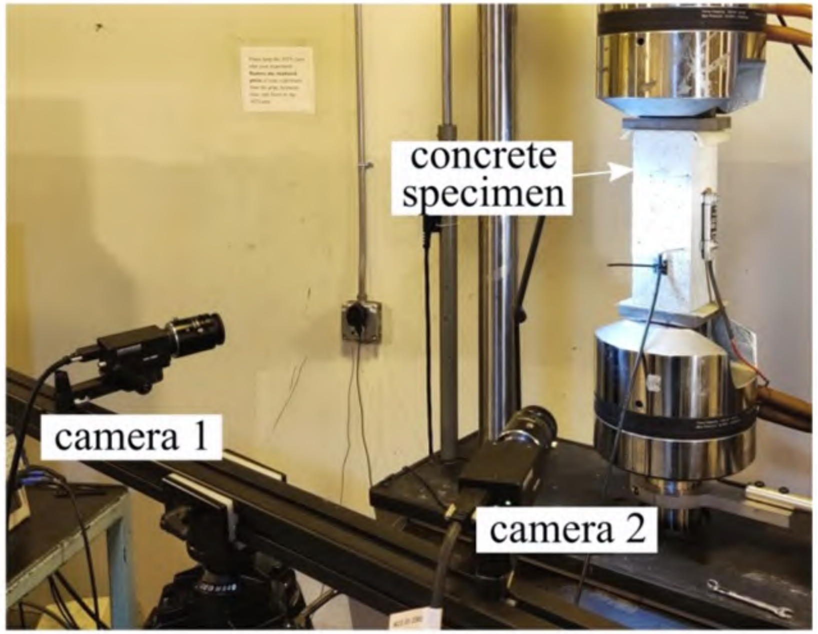
Capacitance as a function of load

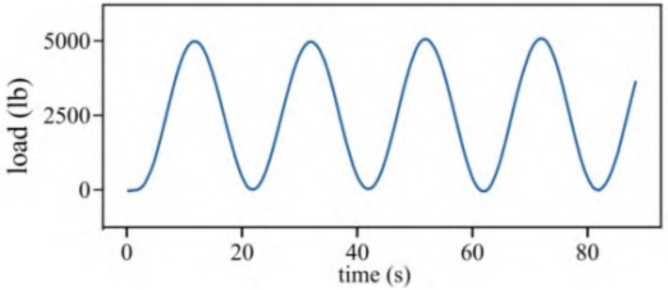


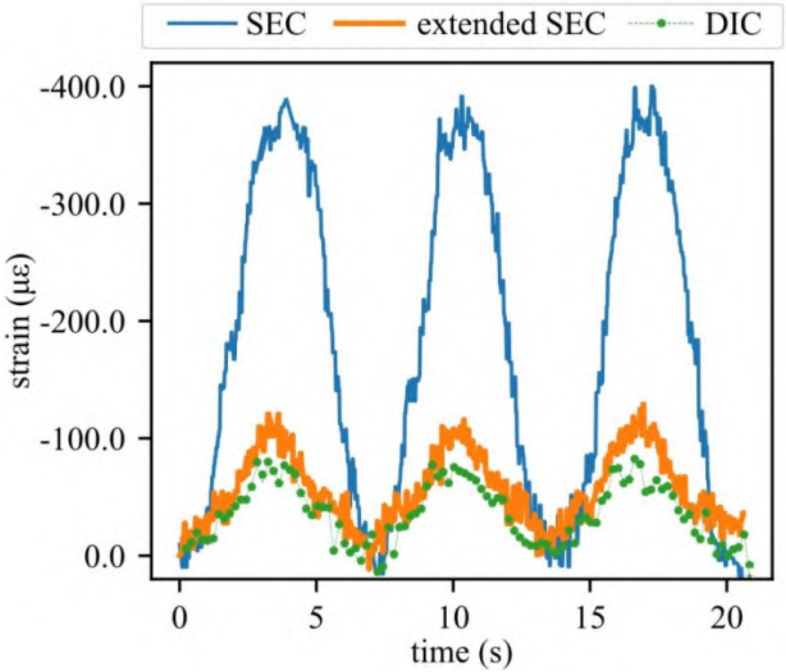
INVESTIGATION 2 : Strain data from three concrete samples



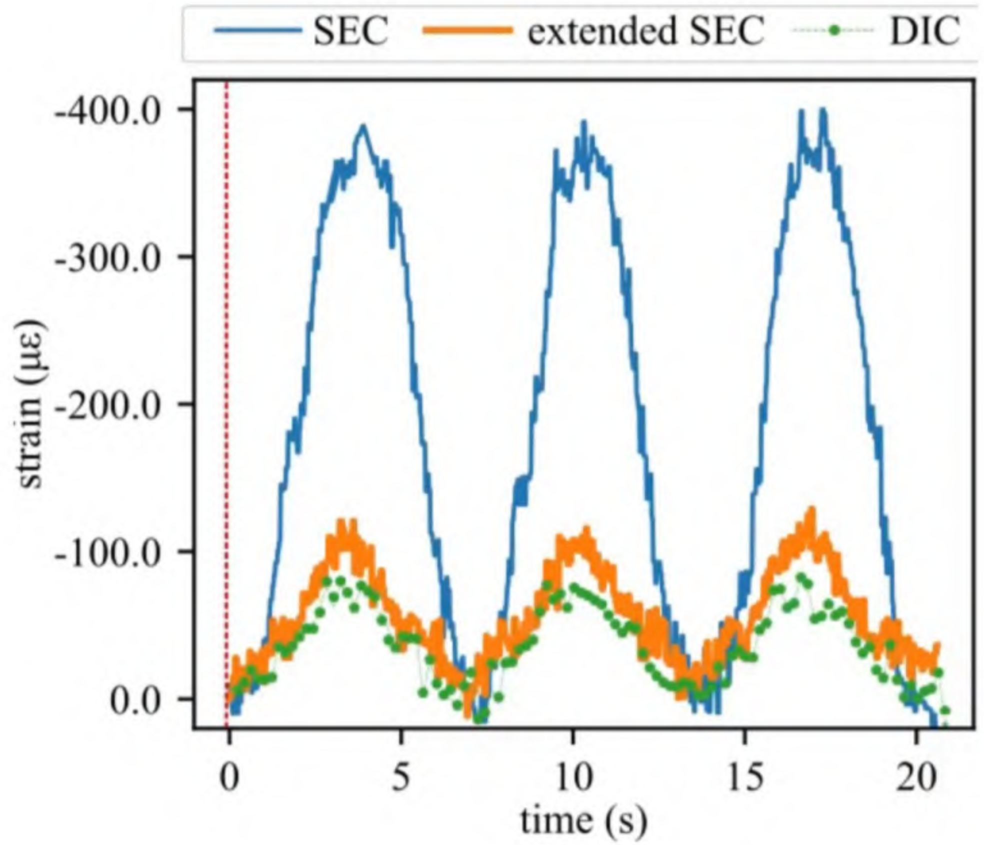
Results and Discussion : DIC Setup and strain data

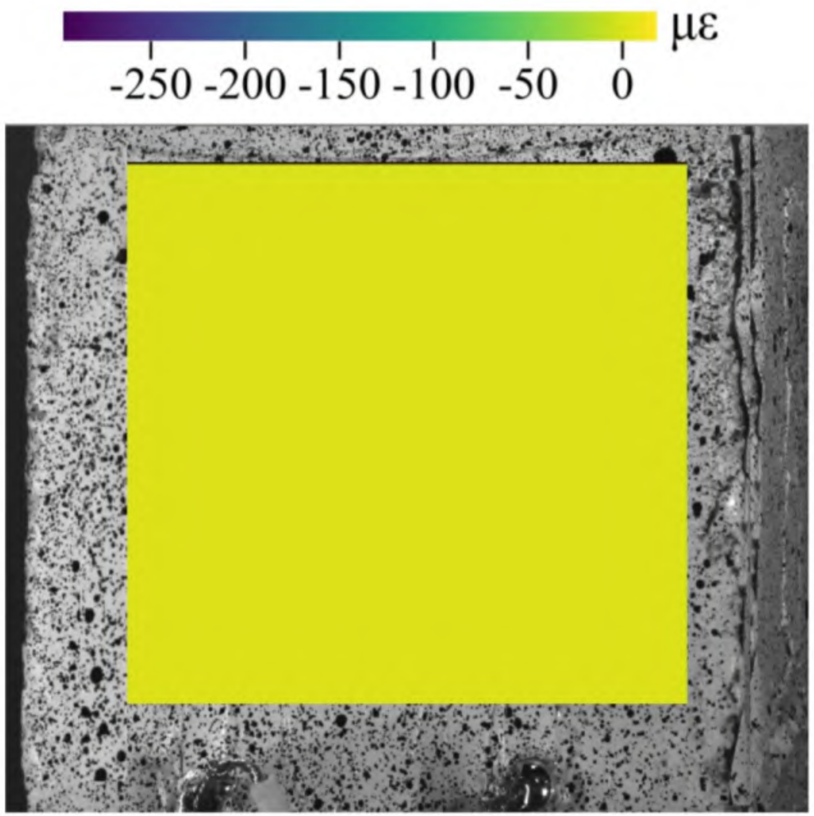




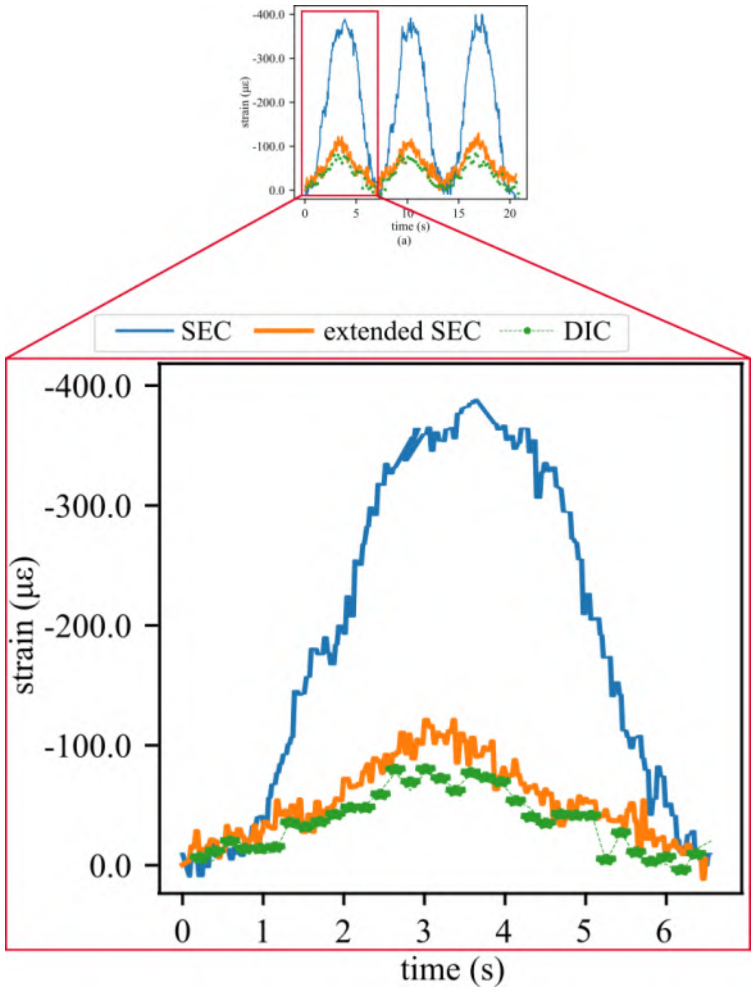


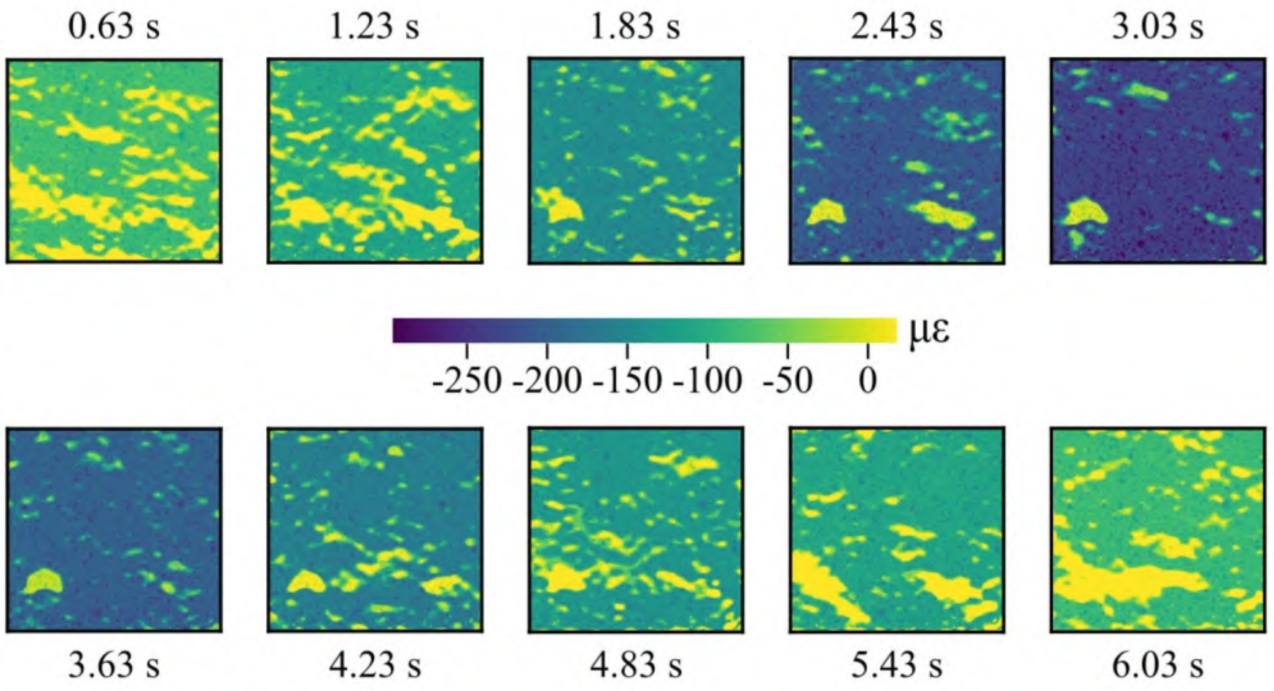
DIC strain investigation



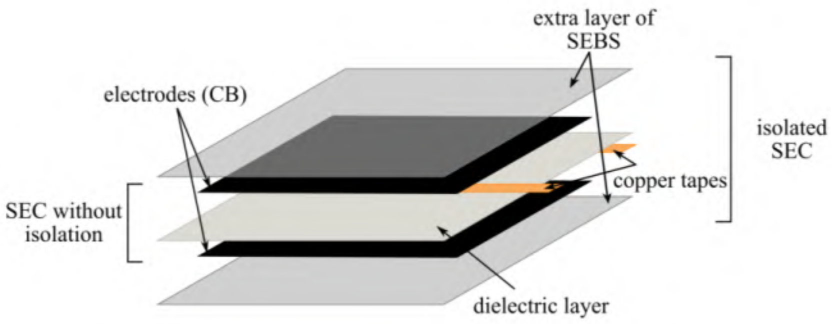


DIC strain data

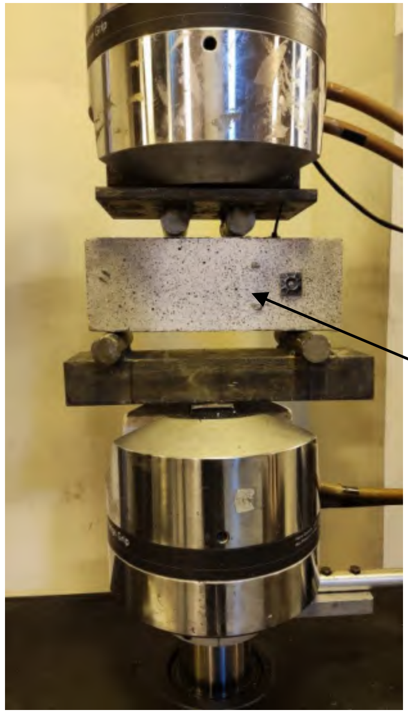




Extended SEC for crack detection/monitoring

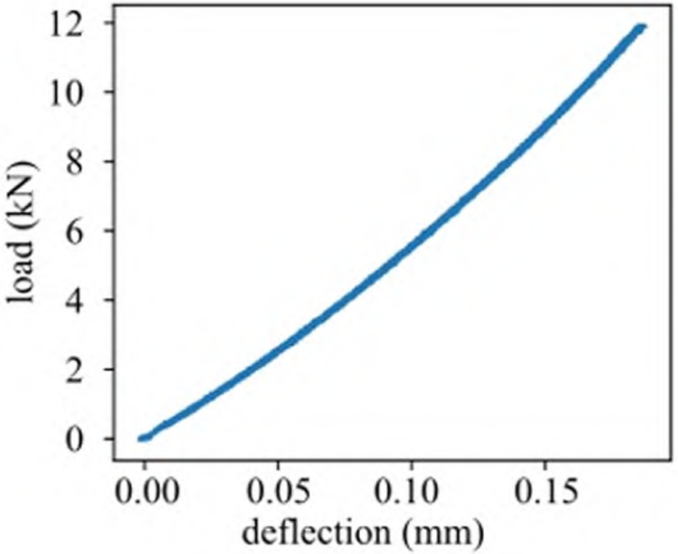


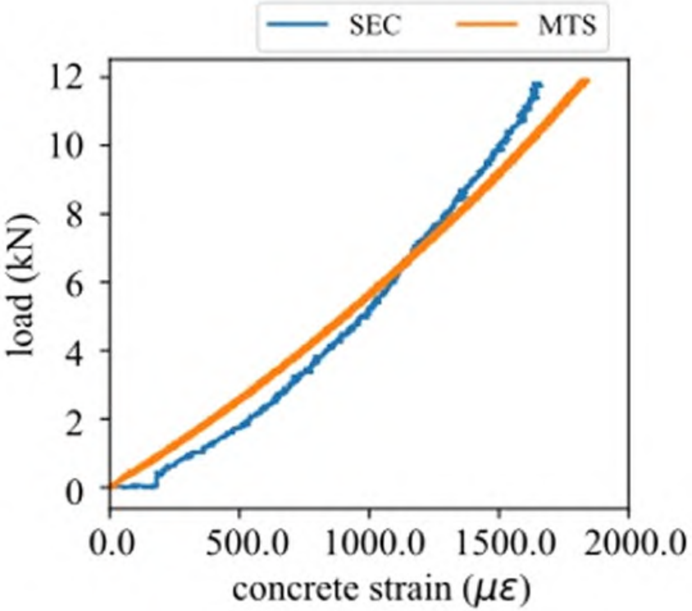
extended SEC



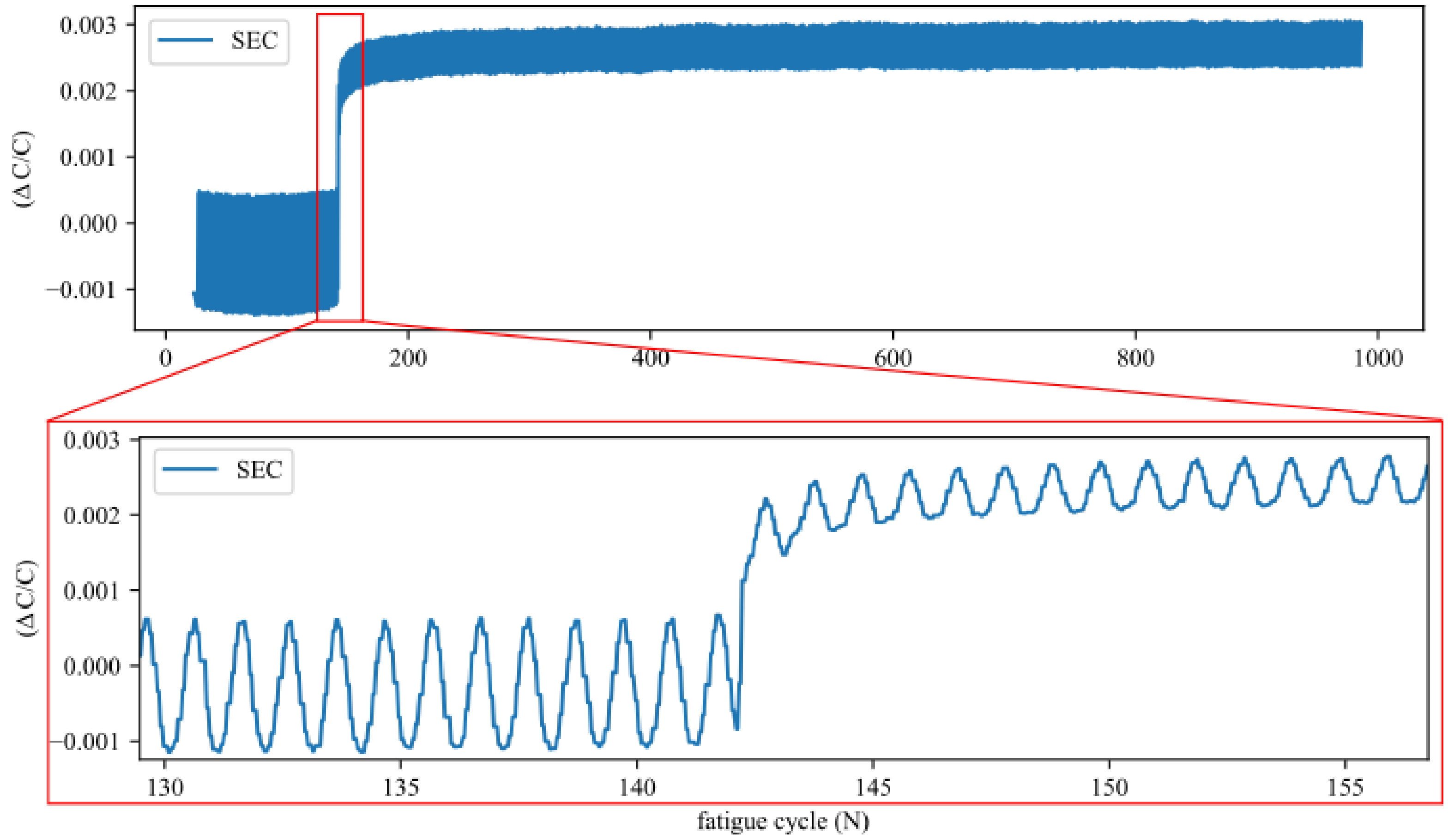
speckled surface with extended SEC

Extended SEC: Response to load

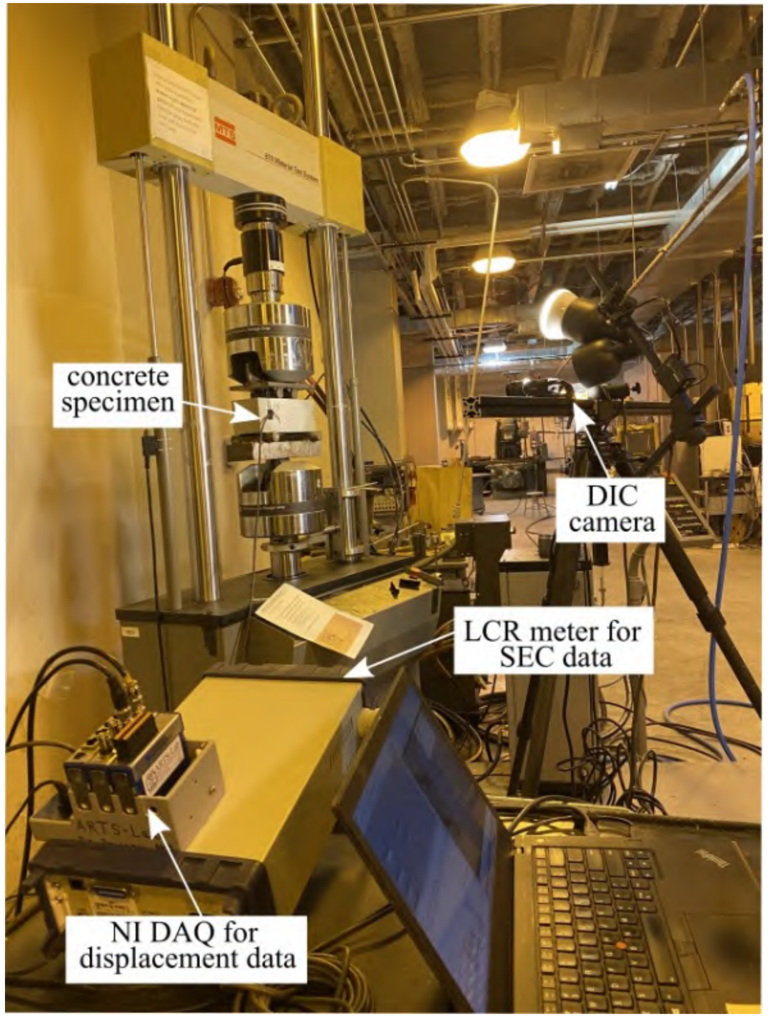




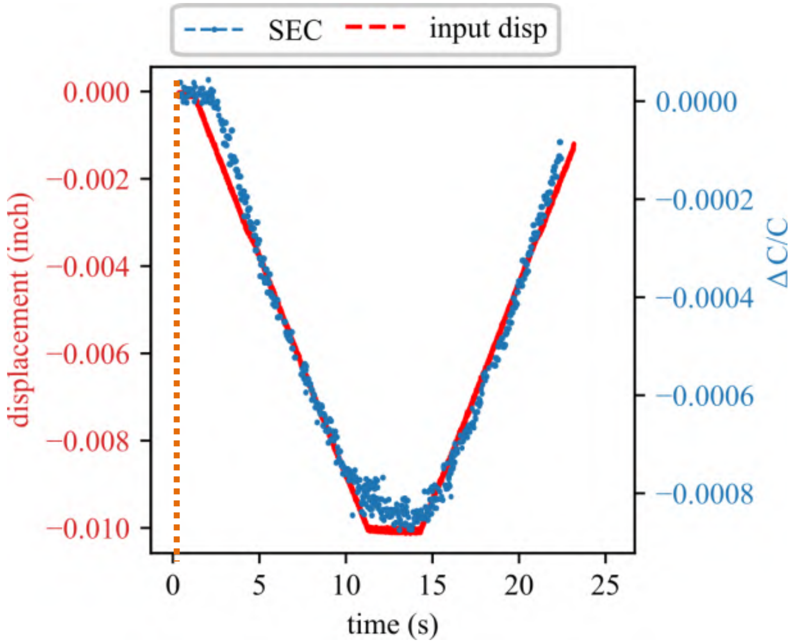
Extended SEC: Crack detection/monitoring

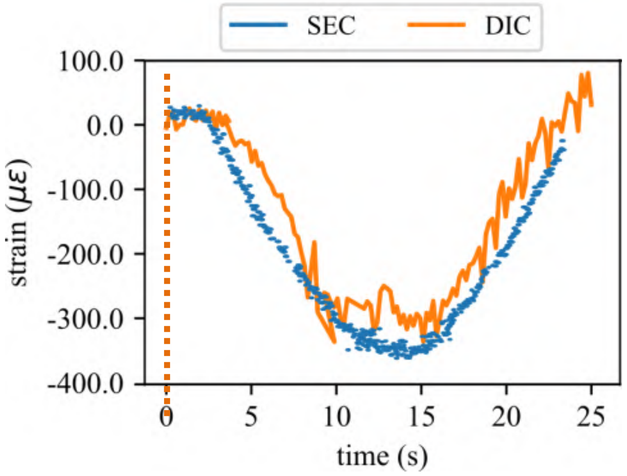


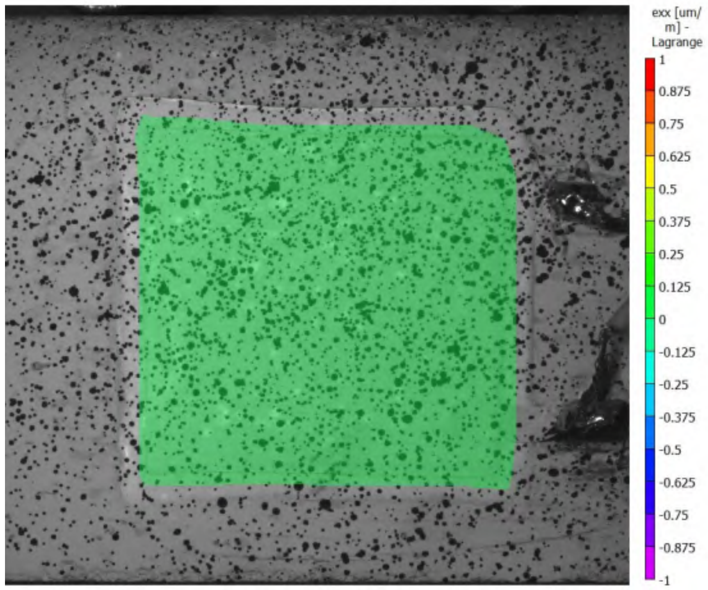
DIC setup for crack monitoring



0.01-inch concrete deflection

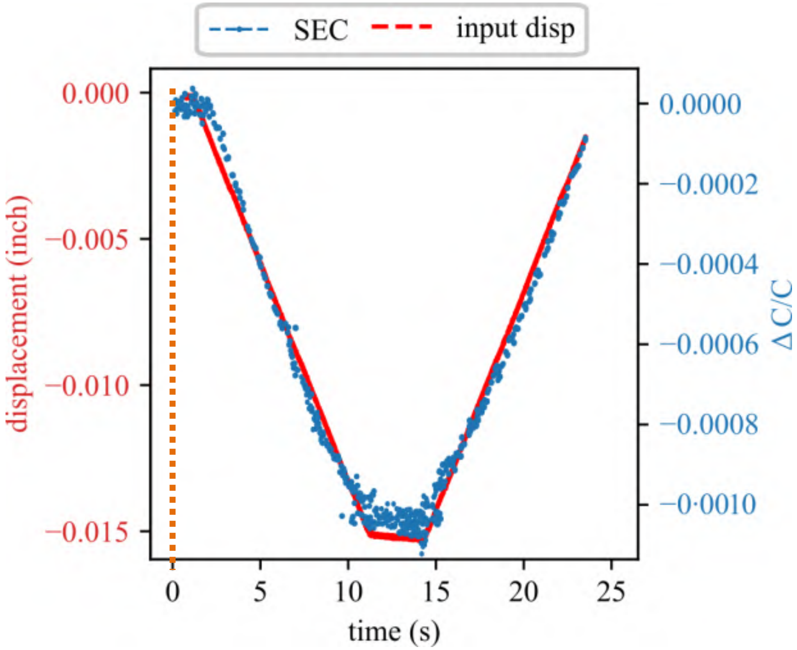


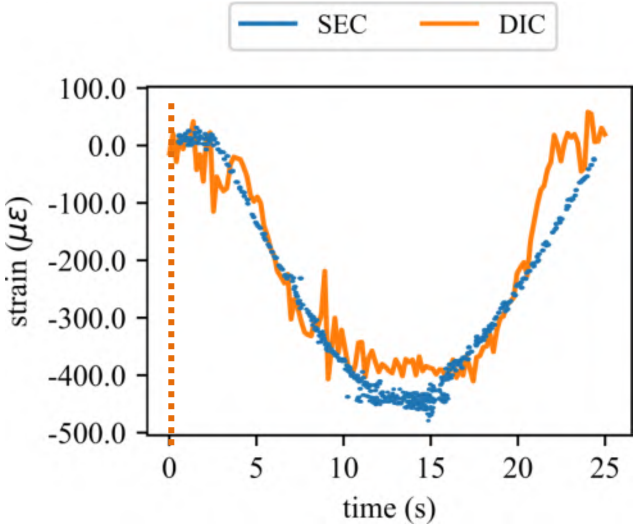


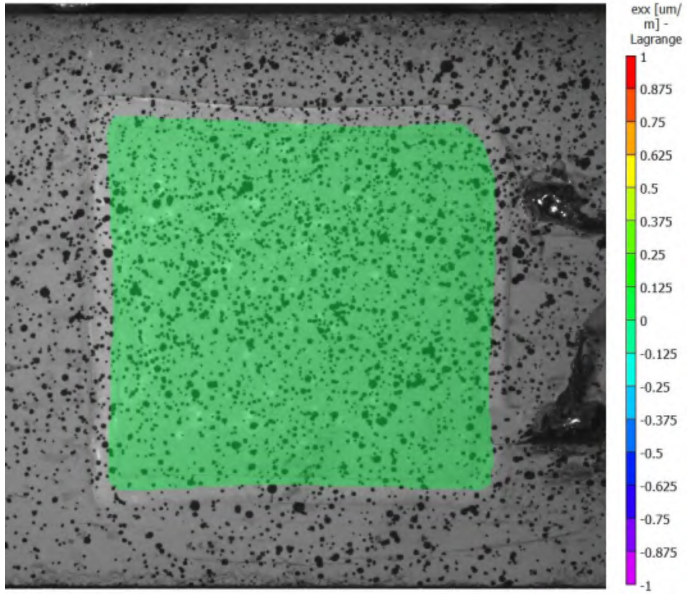


No crack form

0.015-inch concrete deflection

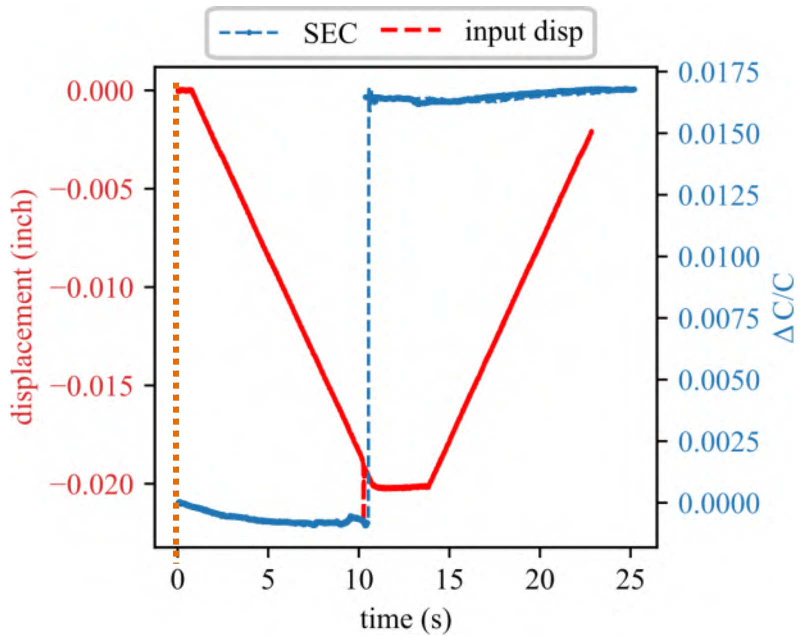


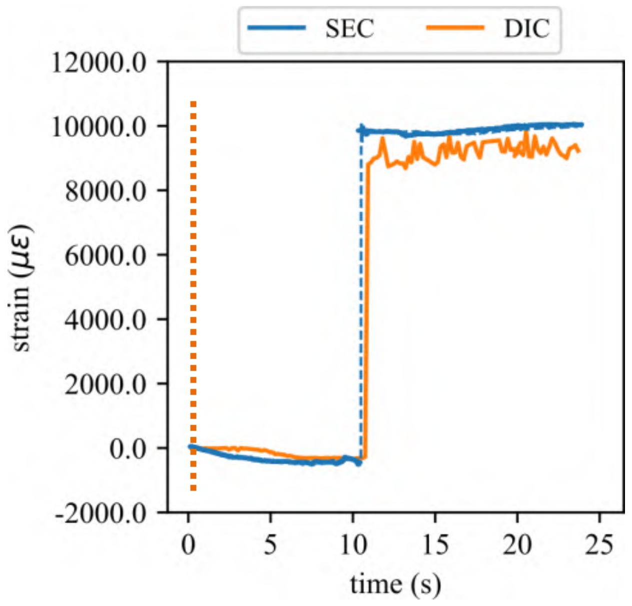


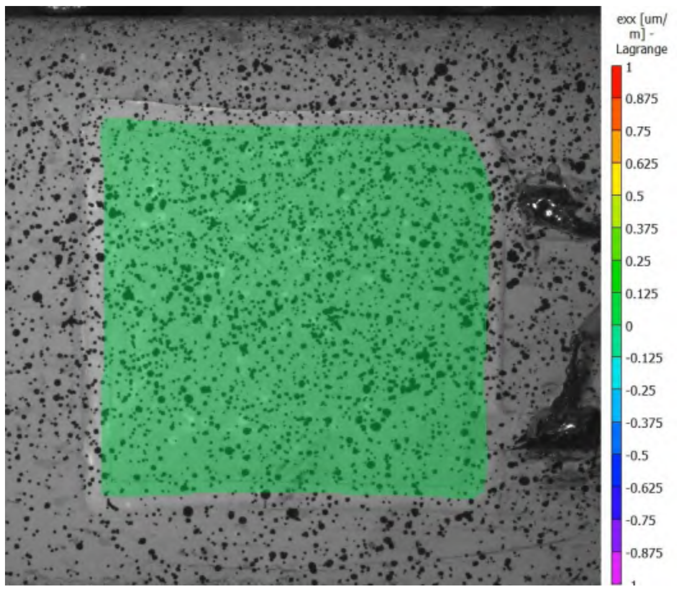


No crack form

0.02-inch concrete deflection







Crack formed at 11 seconds indicated by the jump in capacitance value on the SEC and DIC strain

INVESTIGATION 3

Why and How

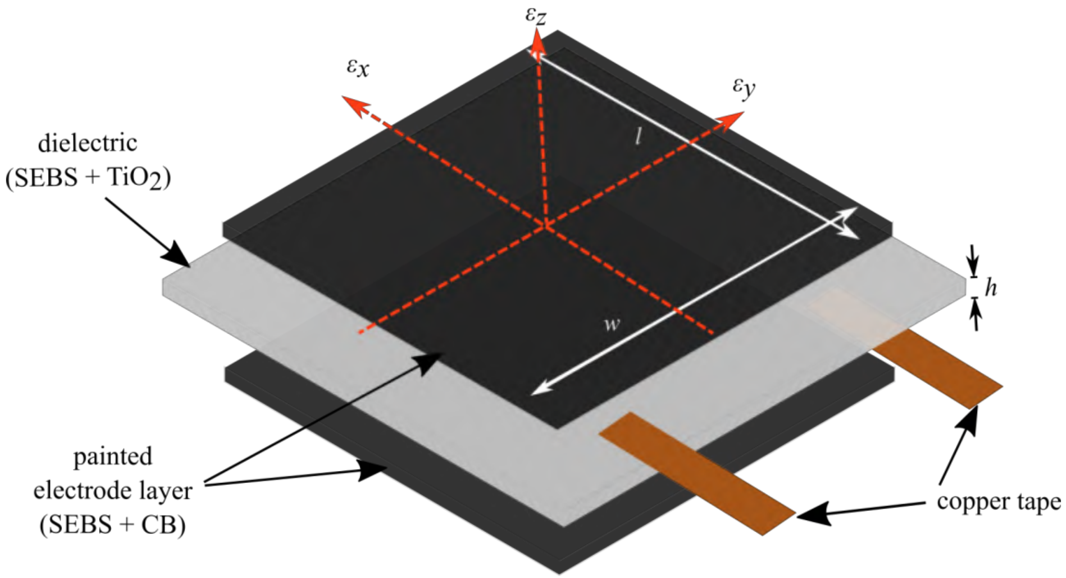
SEC Adhesion investigation

Carbon black solution

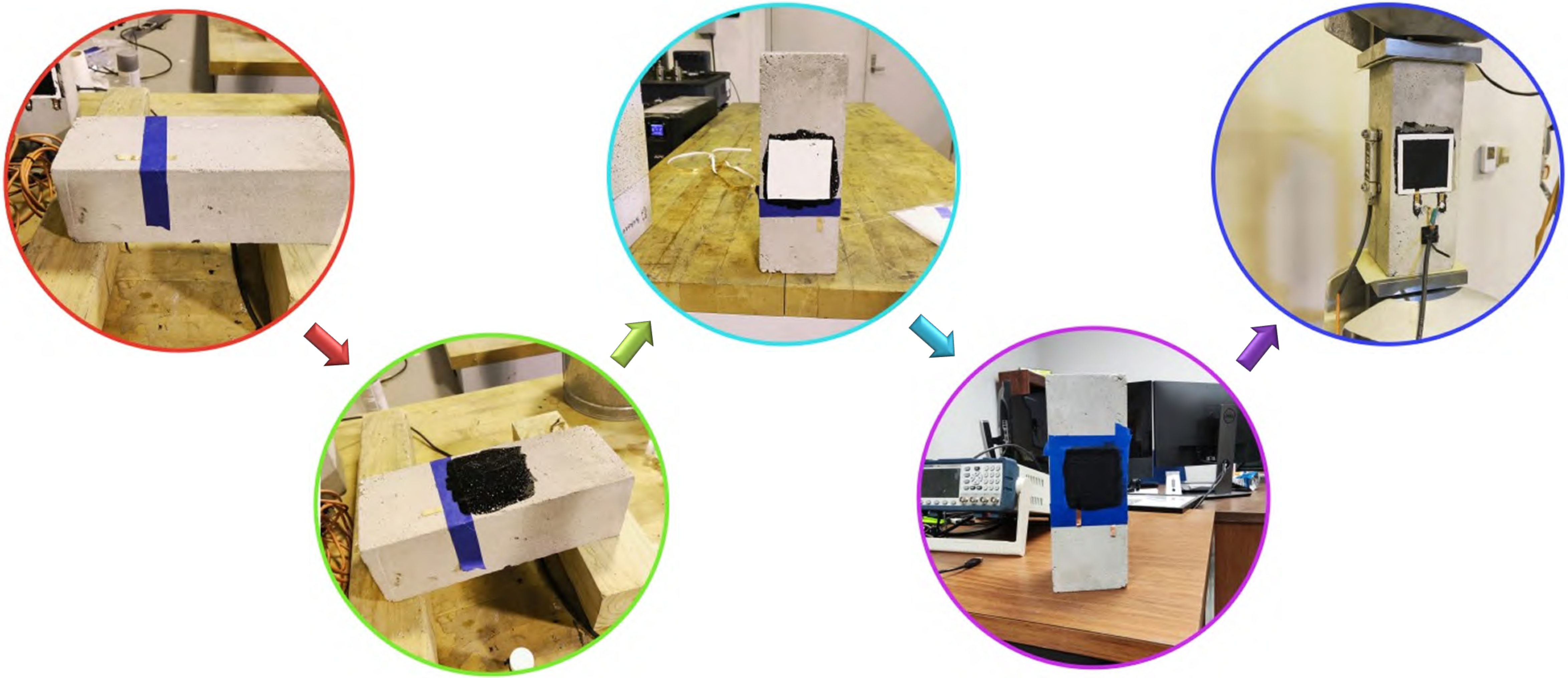
JB weld bi-component adhesive

- Straightforward and cost-effective method
- Expedites sensor deployment (can be sprayed to surface)
- No extra material needed

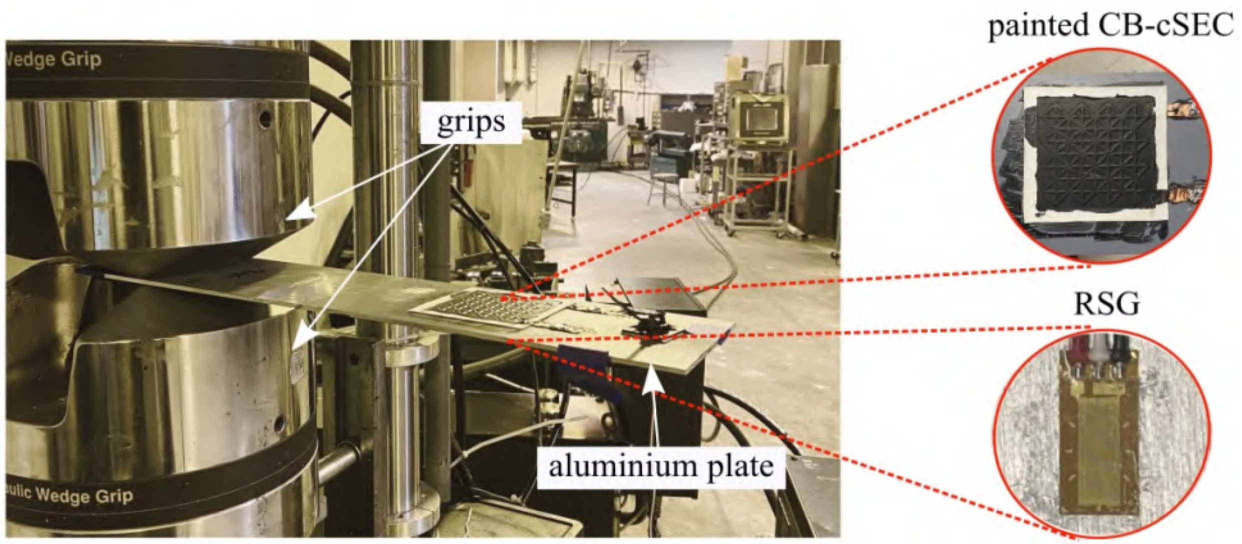
Carbon Black painted SEC



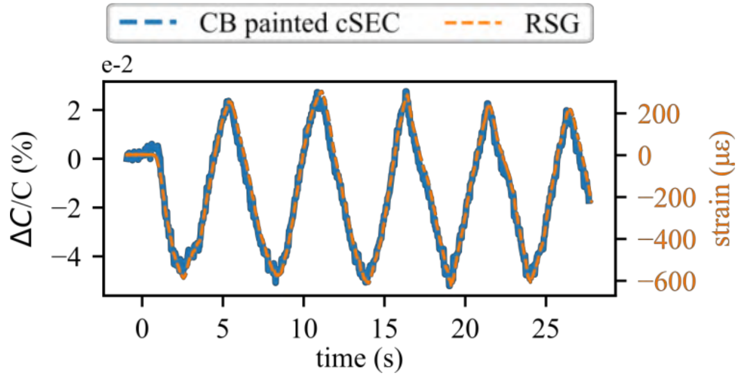
Painting process



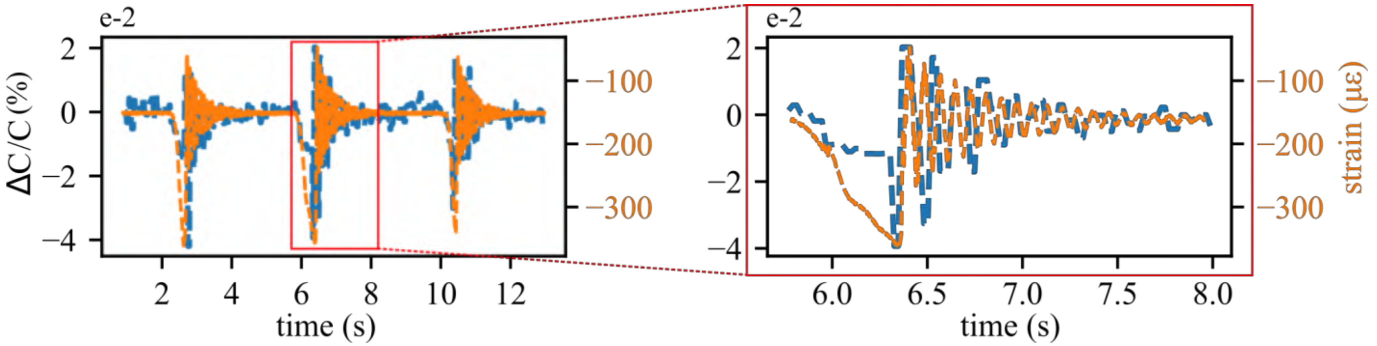
Electromechanical behavior



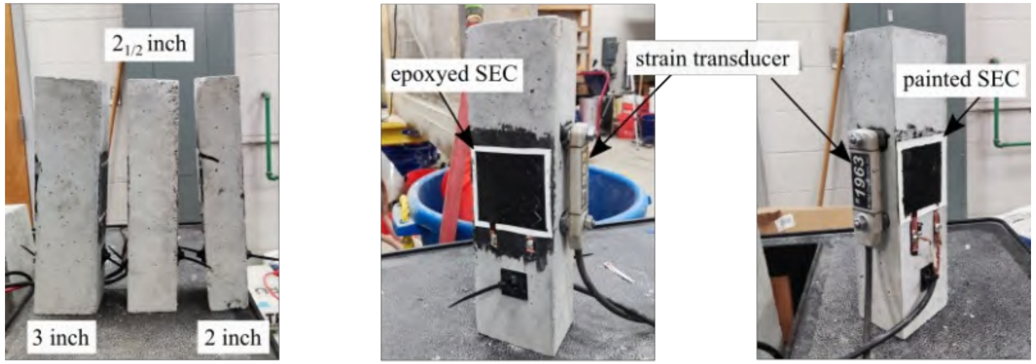
Quasi-static test

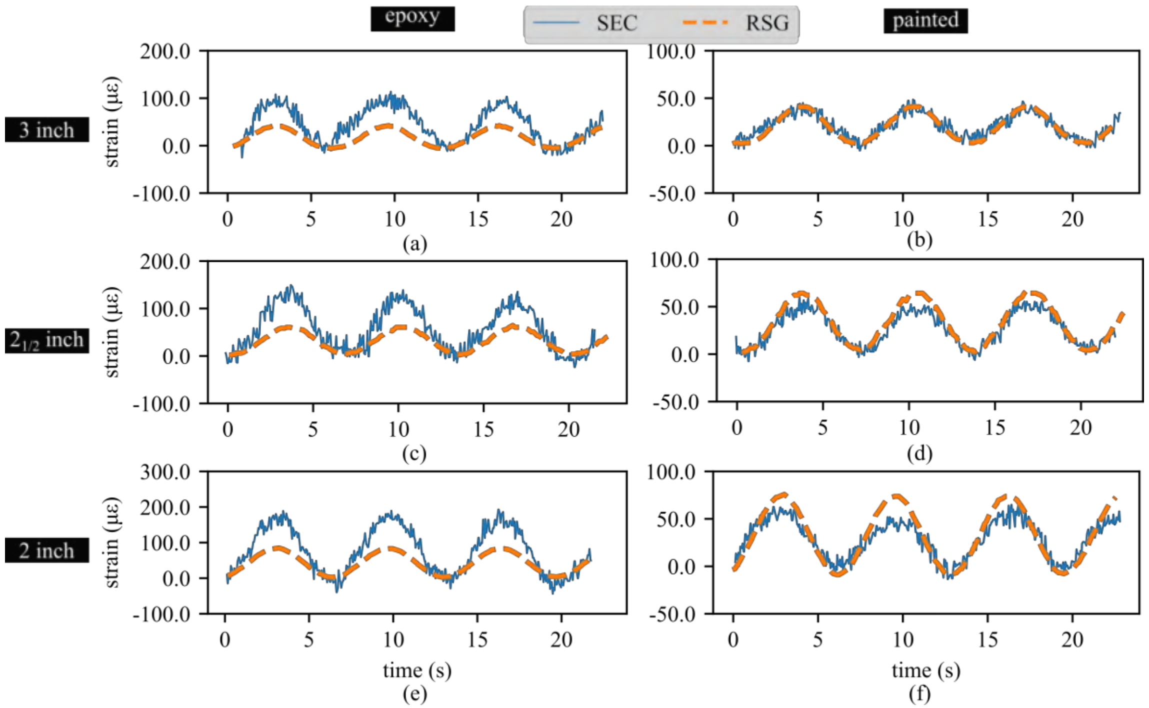


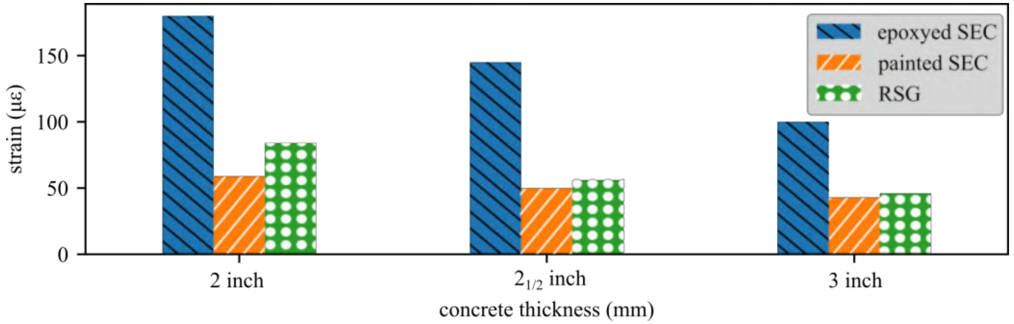
Free vibration test



Strain results on different concrete size



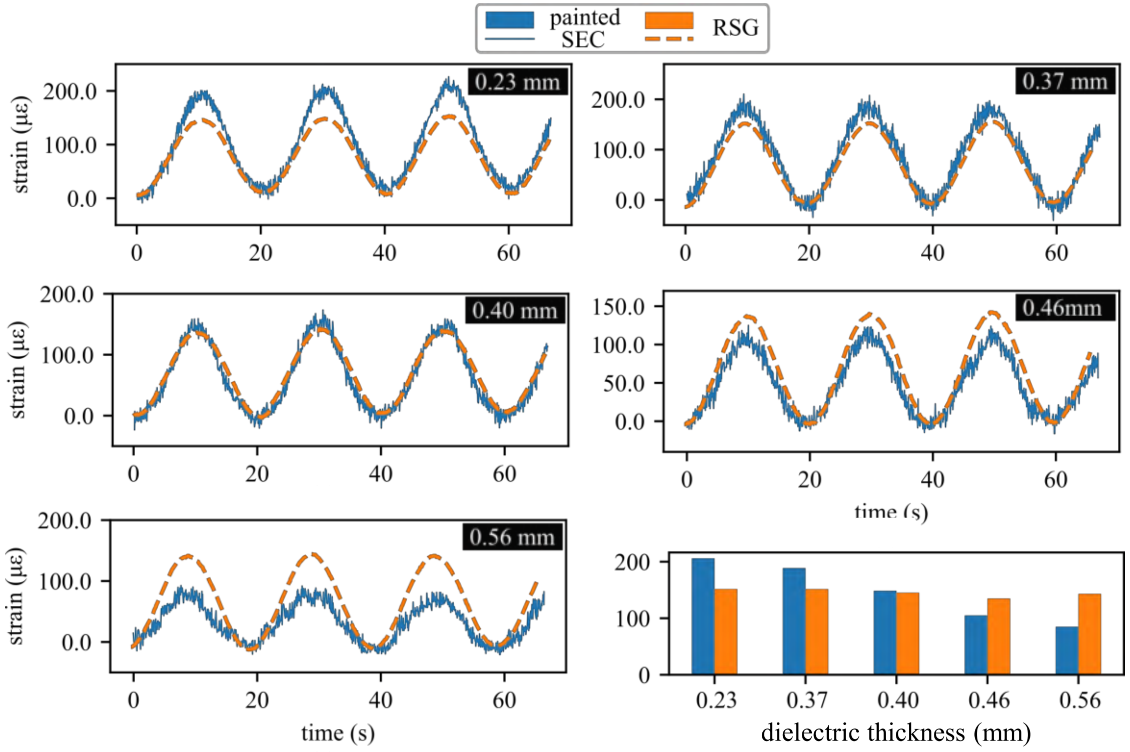




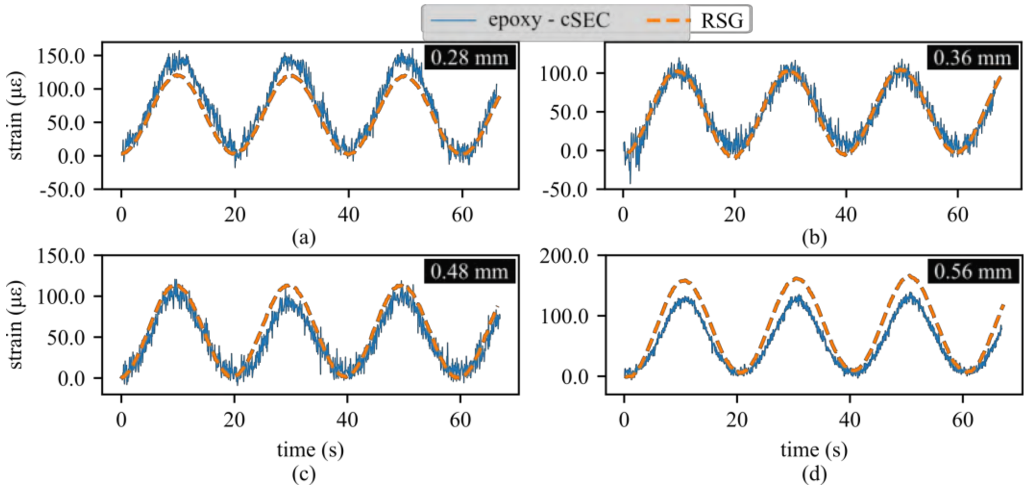
Thickness investigation

- Dielectric layer thickness vs Epoxy SEC thickness

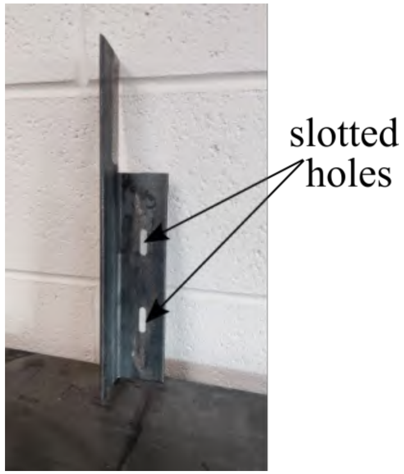
CB-painted SEC

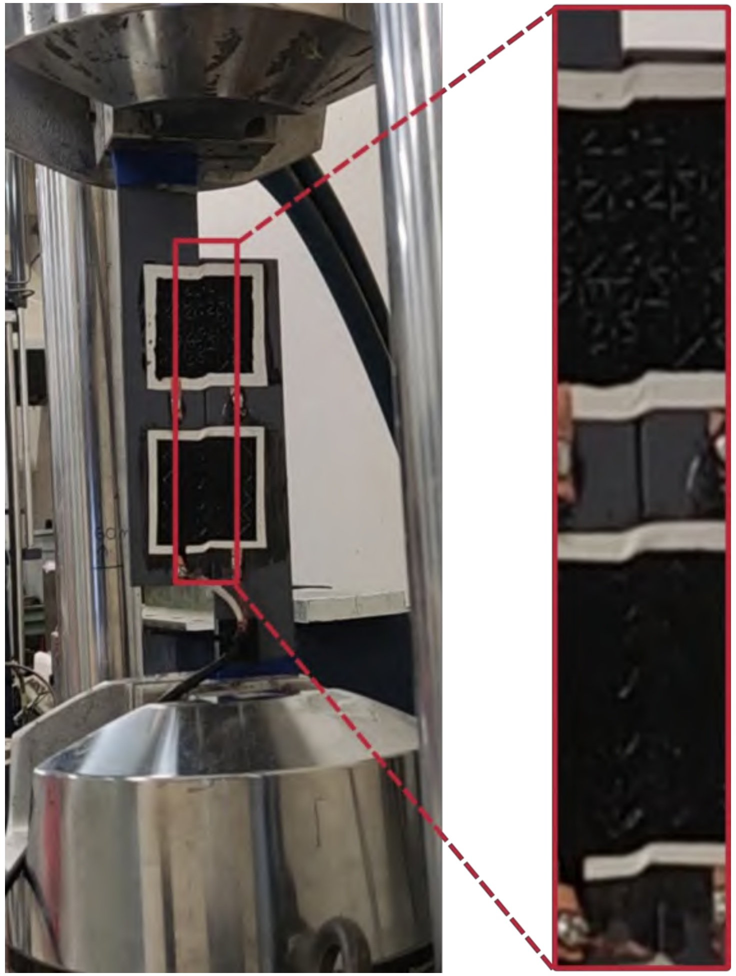


Epoxy SEC



Shear test

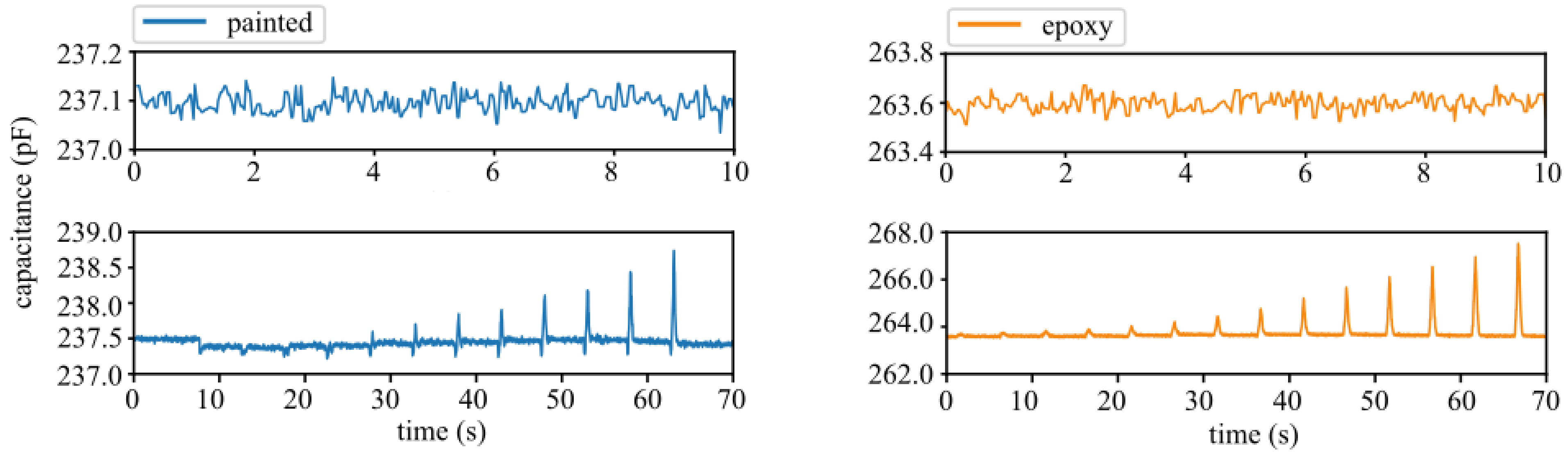


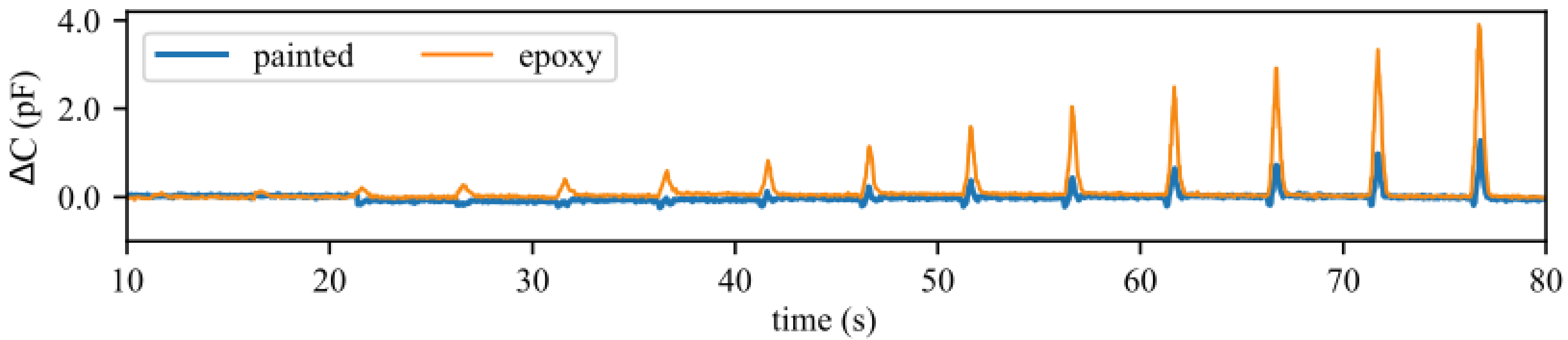


Shear test

Static signal

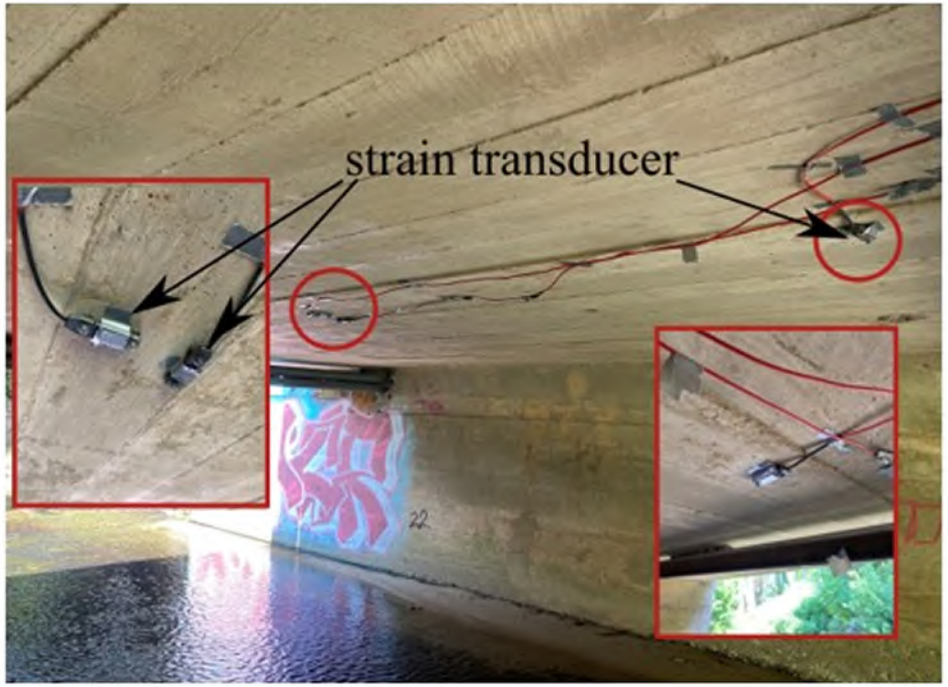
dynamic signal

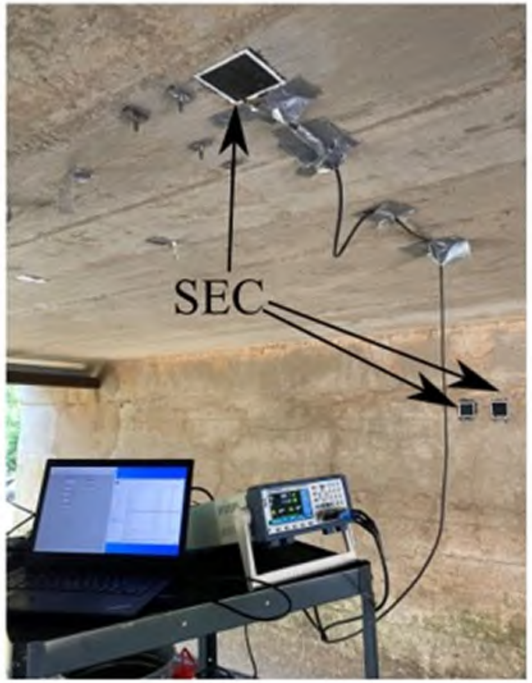




ONGOING WORKS

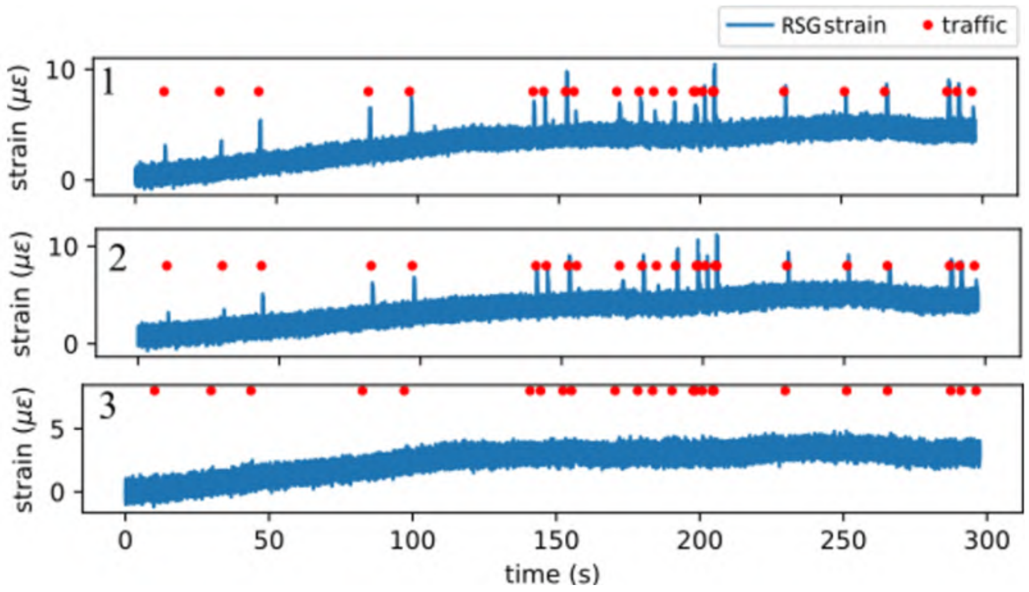
Ongoing works: Bridge sensor deployment

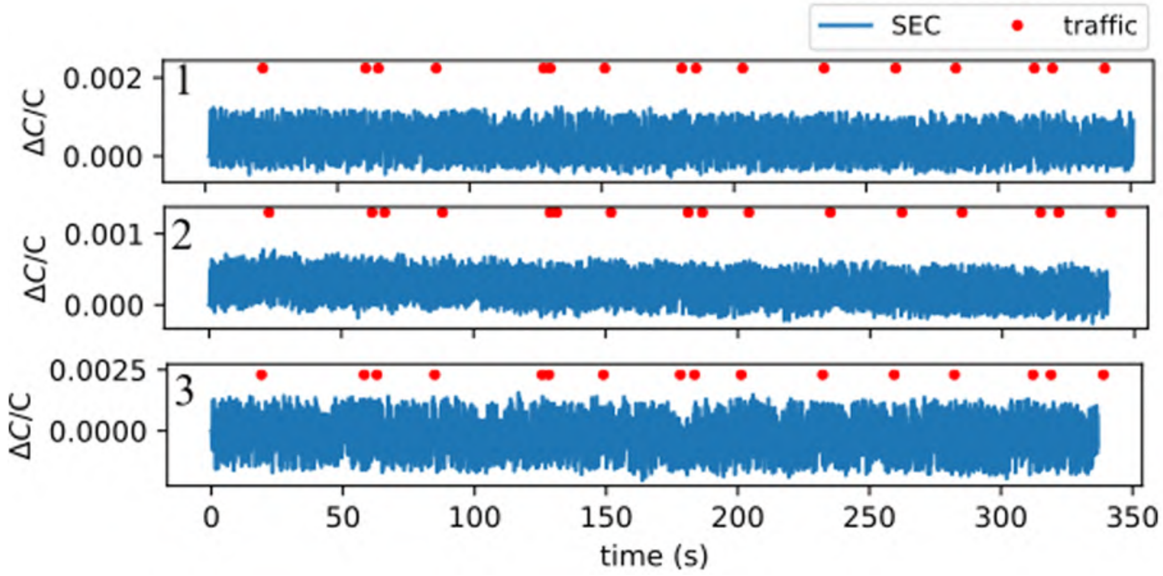




Preliminary results

Traffic monitoring on bridge





CONCLUSION

CONCLUSION

- Effective Reduction of Capacitance Coupling:
  - Successful implementation of a solution to significantly minimize capacitance coupling between the SEC (Strain-Embedded Capacitor) and concrete, leading to enhanced accuracy in strain monitoring.

- Advantages of Modified SEC Design:
  - This study has deepened our understanding of the benefits associated with the modified SEC design, particularly with the incorporation of the extended SEBS (Styrene-Ethylene-Butadiene-Styrene) polymer matrix.

- Lowered Nominal Capacitance:
  - Our investigation has demonstrated that the addition of an extra layer of SEBS results in a notable reduction in the nominal capacitance of the sensor.

- Validation Through Digital Image Correlation:
  - The extended SEC design was rigorously validated using Digital Image Correlation techniques, conclusively illustrating the substantial reduction in capacitive coupling between the sensor and the concrete interface.

- Comparative Analysis for Application Suitability:
  - We have provided comparative insights into the performance of two attachment methods: direct painting and epoxy bonding. This analysis serves as a guide to determine the most suitable method based on specific application needs.

PUBLICATIONS FROM THIS WORK

1. **Emmanuel Ogunniyi**, Alexander Vereen, Austin RJ Downey, Simon Laflamme, Jian Li, Caroline Bennett, William Collins, Hongki Jo, Alexander Henderson, and Paul Ziehl. Investigation of electrically isolated capacitive sensing skins on concrete to reduce structure/sensor capacitive coupling. *Measurement Science and Technology*, 34(5):055113, 2023.

2. **Emmanuel Ogunniyi**, Han Liu, Austin RJ Downey, Simon Laflamme, Jian Li, Caroline Bennett, William Collins, Hongki Jo, and Paul Ziehl. Soft elastomeric capacitors with an extended polymer matrix for strain sensing on concrete. In *Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2023*, volume 12486, pages 262–270. SPIE, 2023.

3. **Emmanuel Ogunniyi**, Han Liu, Austin RJ Downey, Simon Laflamme, Jian Li, Caroline Bennett, William Collins, Hongki Jo, Alexander Henderson, and Paul Ziehl. Enhancing Structural Health Monitoring with direct coated Carbon Black on monitored surface for Elastomeric Capacitors adhesion (Not yet submitted)

ACKNOWLEDGEMENT

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