LARGE AREA CAPACITIVE SENSORS FOR IMPACT DAMAGE MEASUREMENT

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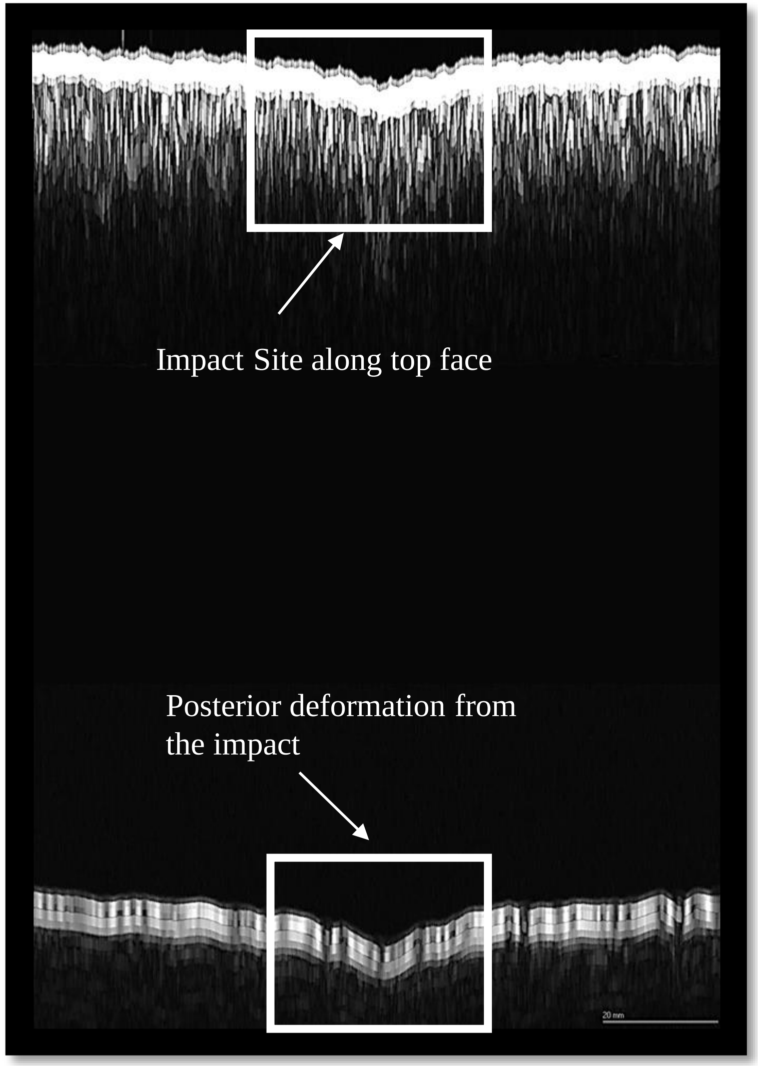
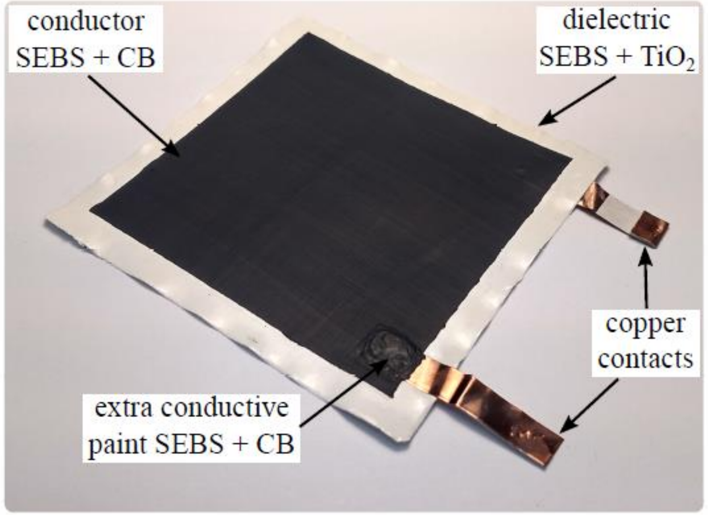
INTRODUCTION

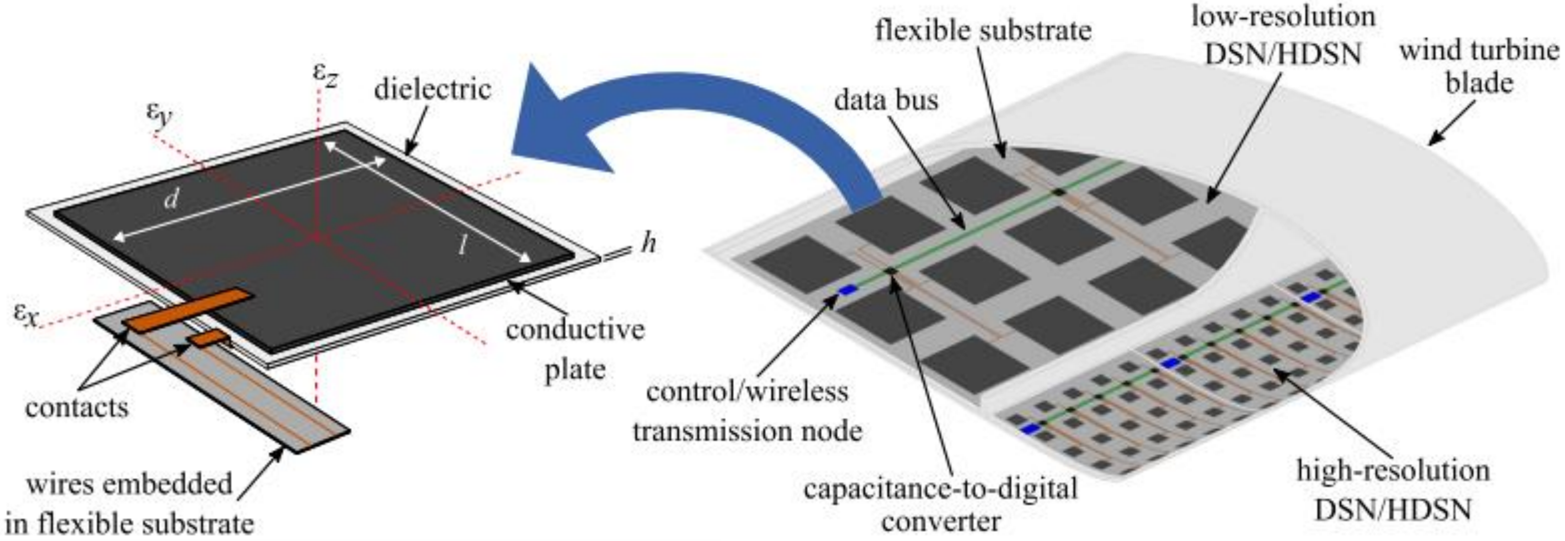
1. Impact damage in composites can induce damage that can dramatically effect toughness of the material.
2. The magnitude of the loss of toughness not apparent on visual inspection of the material
3. NDT methods commonly incur non-trivial opportunity costs while parts are imaged
    - Ultra-sonic
    - Acoustic Emission
    - Radiography



Ultrasonic image of composite blowout damage courtesy of iMAP's lab U of SC.

BACKGROUND





The soft elastomeric capacitor (SEC) is a flexible electronic capable of monitoring strain over large areas as a singular sensor or as a networked applications. The sensor benefits strongly from measuring the sum of strain along the plane allowing the capture of strain.

Downey et al. "Experimental wind tunnel study of a smart sensing skin for condition evaluation of a wind turbine blade." Smart Materials and Structures 26.12 (2017): 125005.

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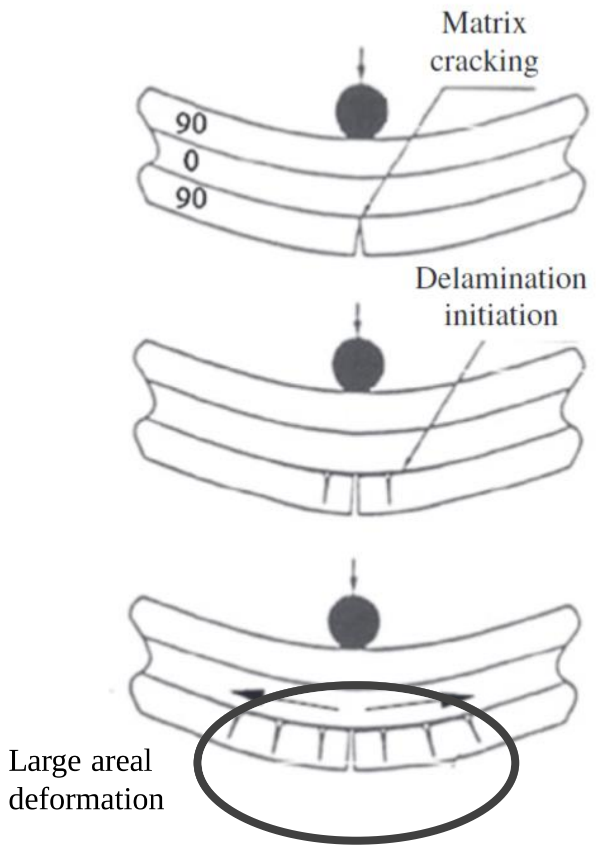
SOFT ELASTOMERIC CAPACITOR FOR IMPACTS

The soft elastomeric capacitor or SEC is a state-based sensor that can describe the aggregate strain under the bonded area. The sensor benefits strongly from measuring the sum of strain along the plane allowing the capture of strain. The sensor measures strains that would induce delamination in other sensors due to its large bonding area. Allowing the study of cracking and more in the field of composites.



Bouvet et al. Low velocity impact modeling in composite laminates capturing permanent indentation.(2012) Composites Science and Technology, vol. 72 (n° 16). pp. 1977-1988. ISSN 0266-3538

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THE SOFT ELASTOMERIC CAPACITOR

- 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

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BACKGROUND

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

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

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

Normalized difference in capacitance

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

Definition of strain

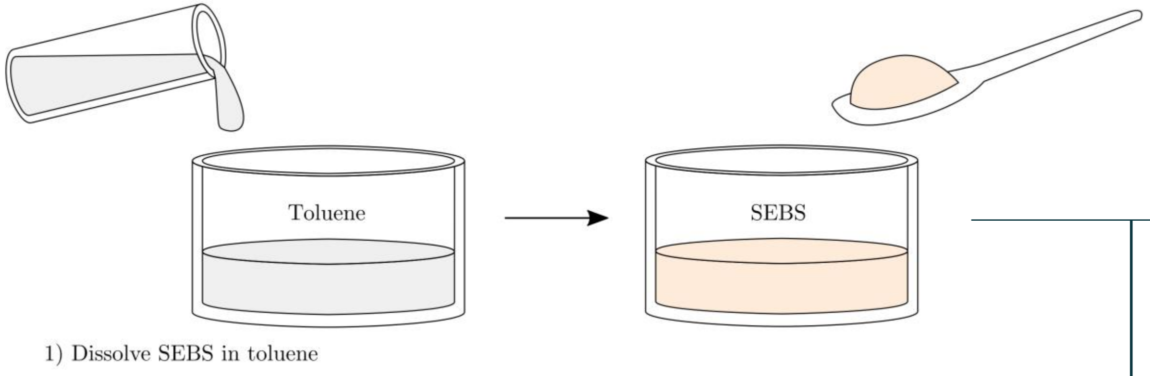
$$\varepsilon_{\mathrm{h}} = -\frac{\nu}{E}(\sigma_{\mathrm{l}} + \sigma_{\mathrm{w}}) = -\frac{\nu}{1-\nu}(\varepsilon_{\mathrm{w}} + \varepsilon_{\mathrm{l}})$$

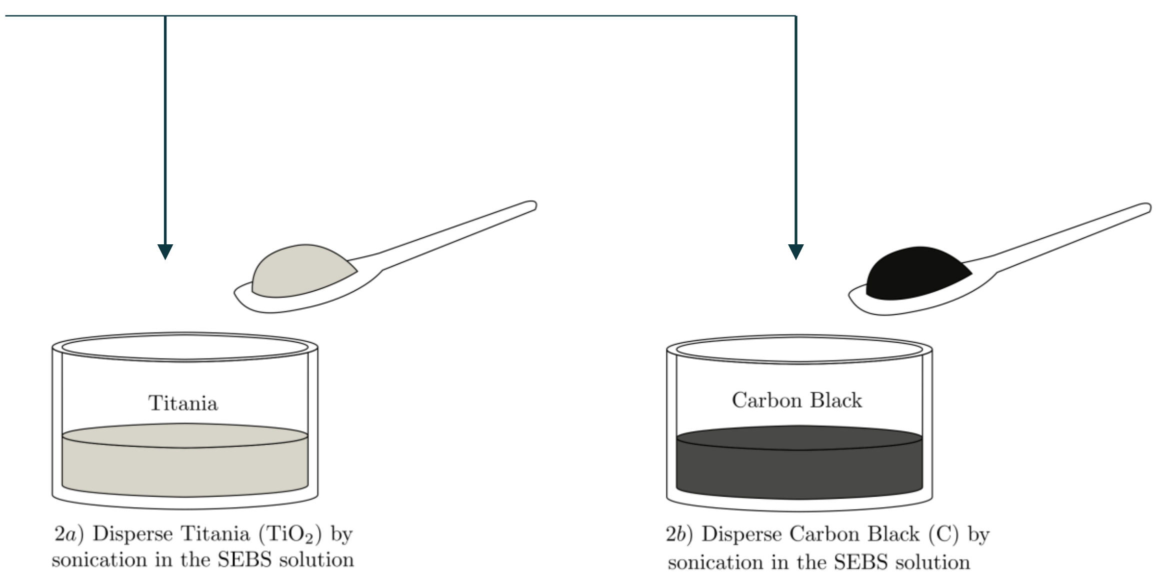
Plane stress assumption

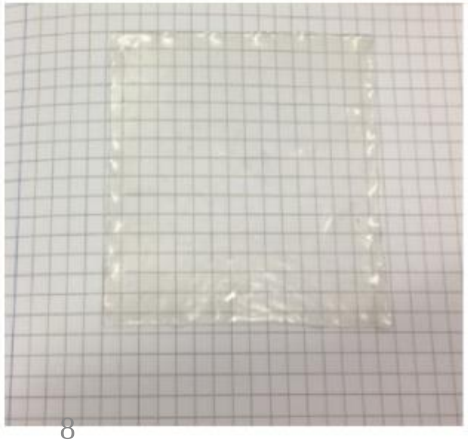
$$\frac{\Delta C}{C_0} = \frac{1}{1-\nu}(\varepsilon_{\mathrm{l}} + \varepsilon_{w})$$

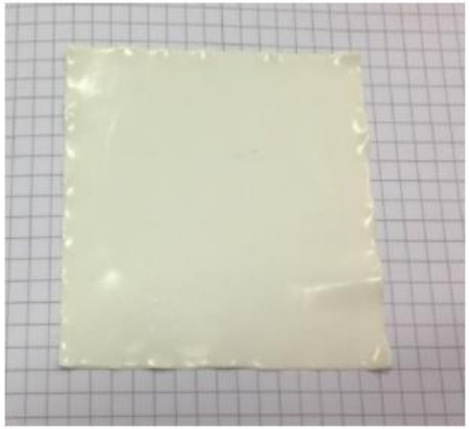
Capacitance in areal deformation

MANUFACTURE









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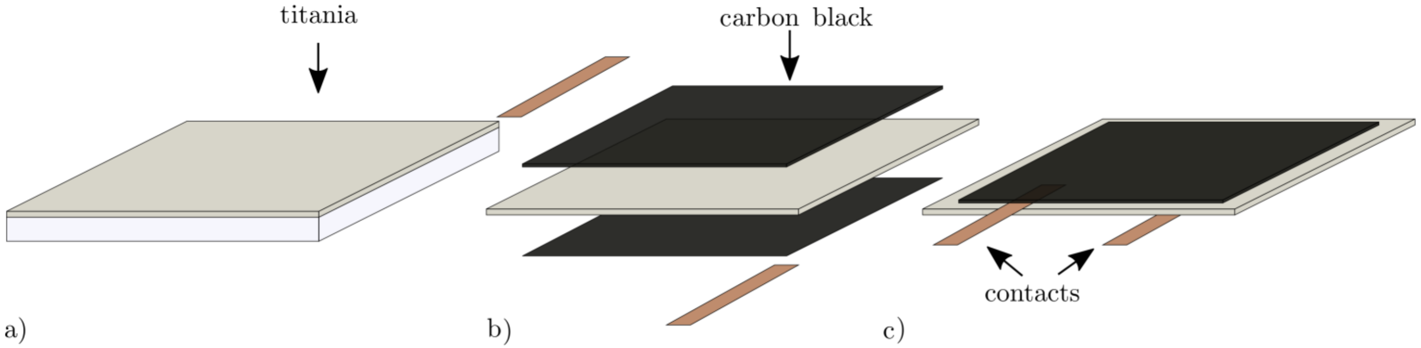
MANUFACTURE



a) The dielectric is drop cast onto a glass pane
b) The carbon black SEBS solution is then painted onto the dielectric in progressive layers
c) Two copper tabs are used for metallic connections to connect to the data acquisition system

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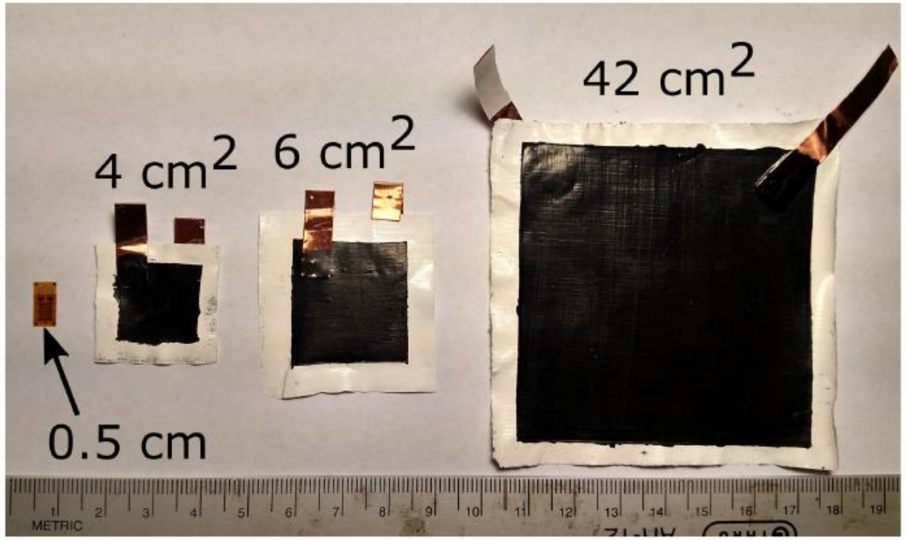
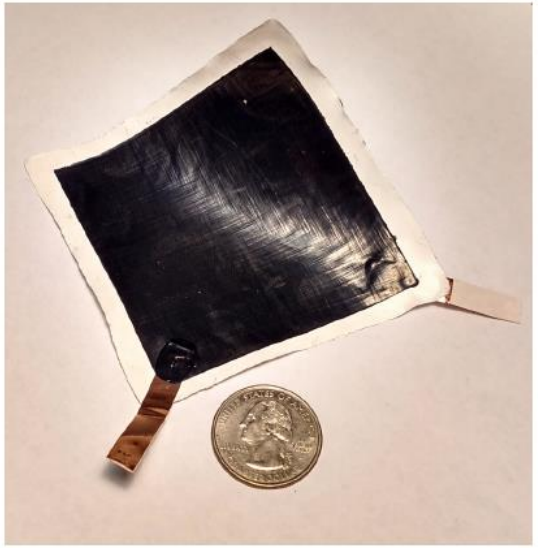
PROPERTIES

- The manufacture of the SEC makes the scaling of the sensor trivial
- The Elastomer matrix can extend up to 500% its original length





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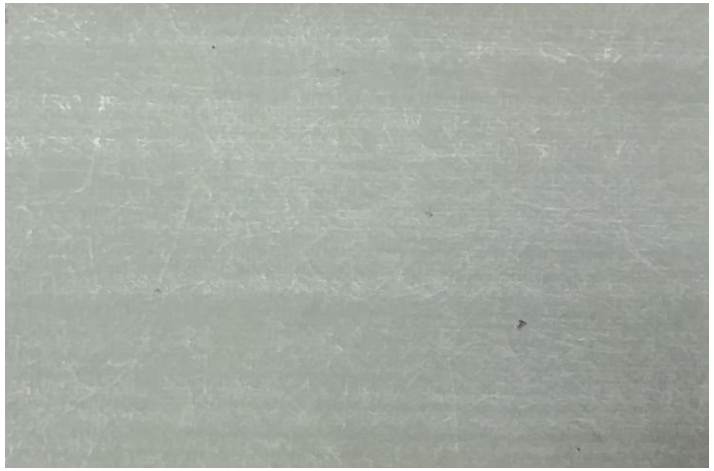
STUDY MATERIAL

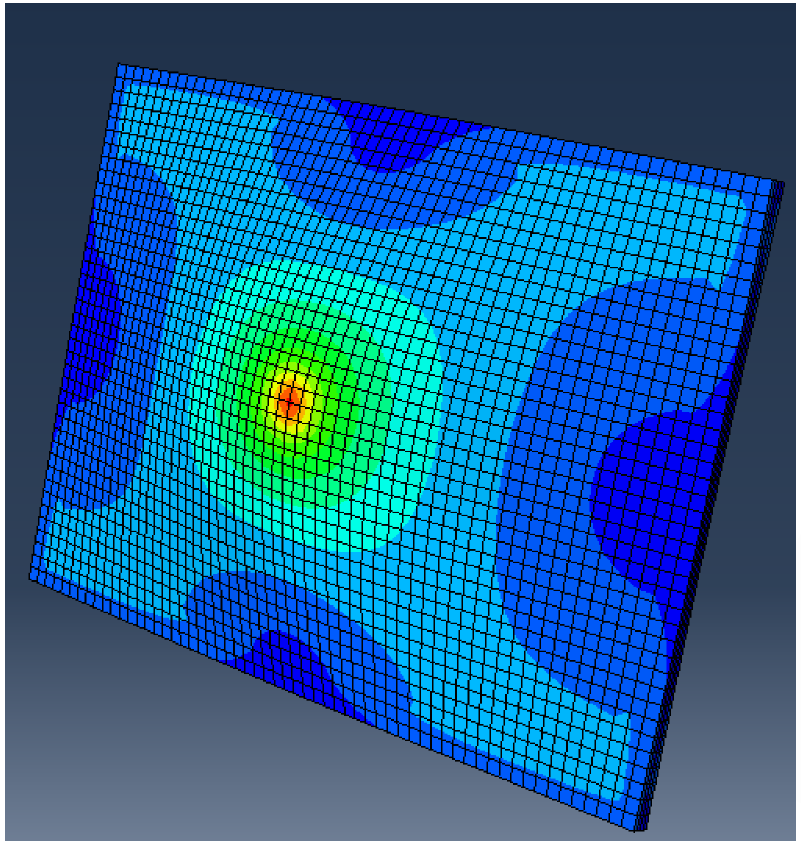
Glass Fiber Reinforced Plastic or (GFRP):

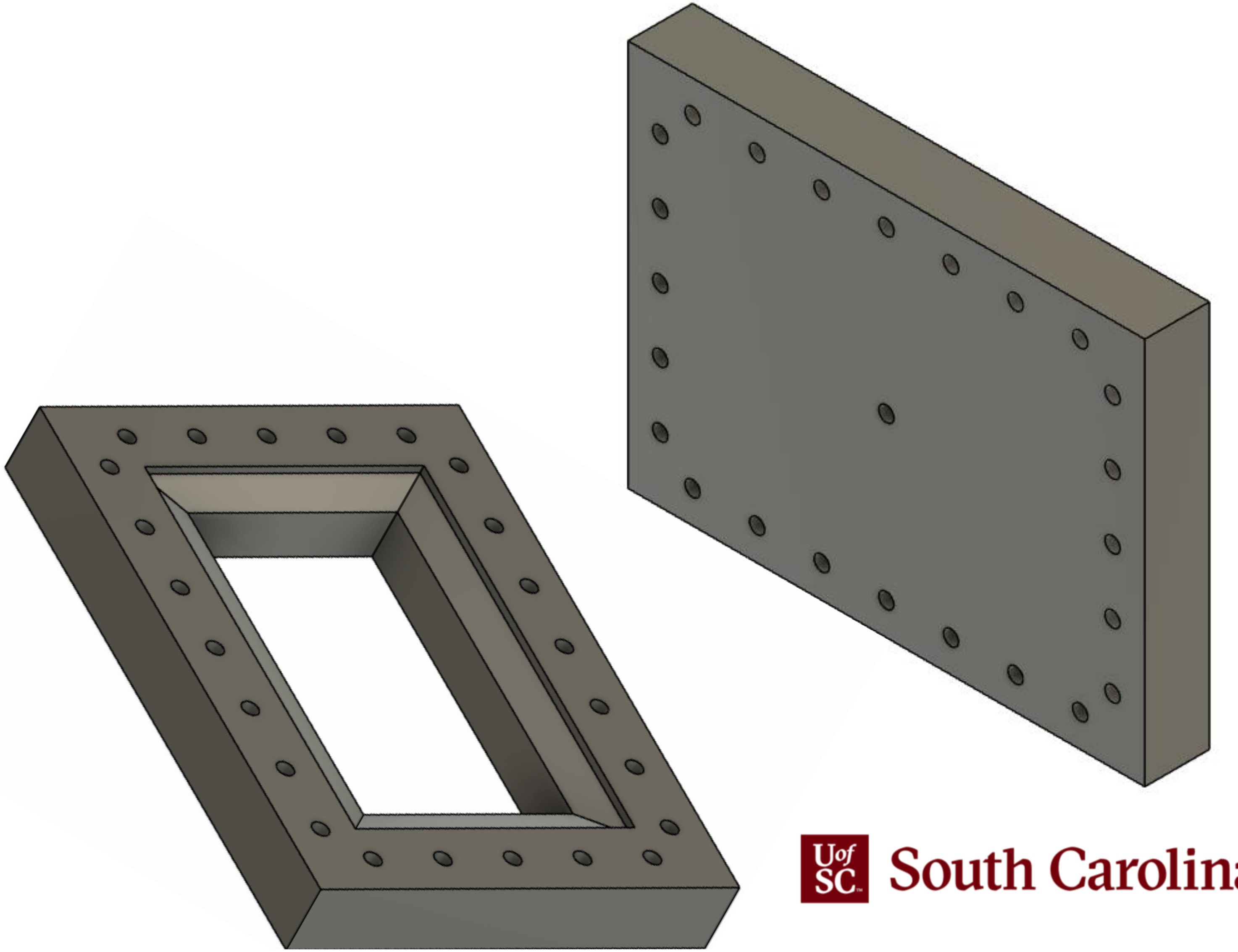
- Fiber orient: Random
- Fiber length: Short
- Matrix: Polyester
- Fiber material: Glass
- Dimension: [4 x 6 x 0.125] in^3



OUT OF PLANE VERIFICATION

SUPPORTING FEA INVESTIGATION





SUPPORTING FEA INVESTIGATION

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

Parallel plate capacitor

$$\frac{\Delta C}{C_0} = \frac{\left(\frac{A_1}{h_1} - \frac{A_0}{h_0}\right)}{\frac{A_0}{h_0}} = \frac{\mathrm{A_1 h_0}}{\mathrm{A_0 h_1}} - 1$$

Normalize difference in capacitance

$$\rho V_1 = \rho V_0 \rightarrow A_1 h_1 = A_0 d_0$$

Preservation of mass

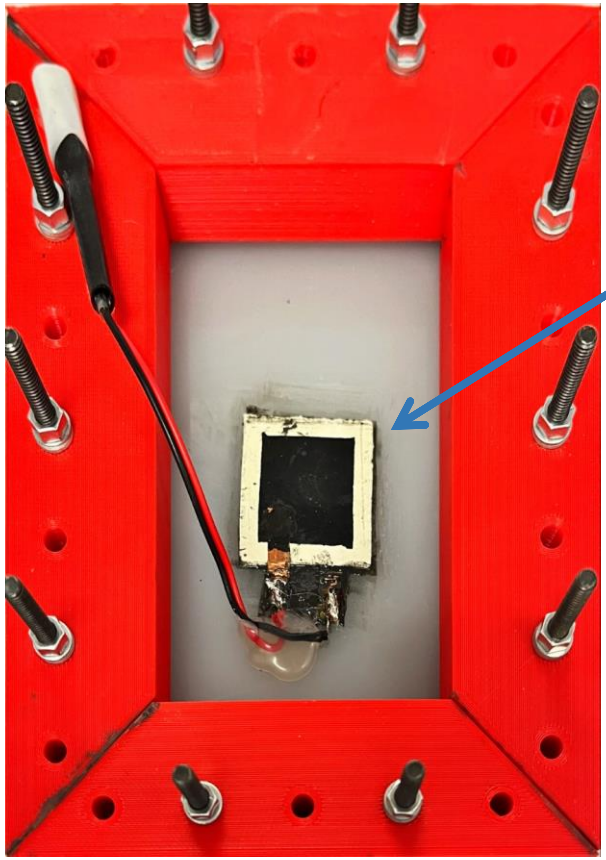
$$\frac{\Delta C}{C_0} = \left(\frac{A_1}{A_0}\right)^2 - 1$$

Normalize difference in capacitance

SUPPORTING FEA INVESTIGATION

displacement condition

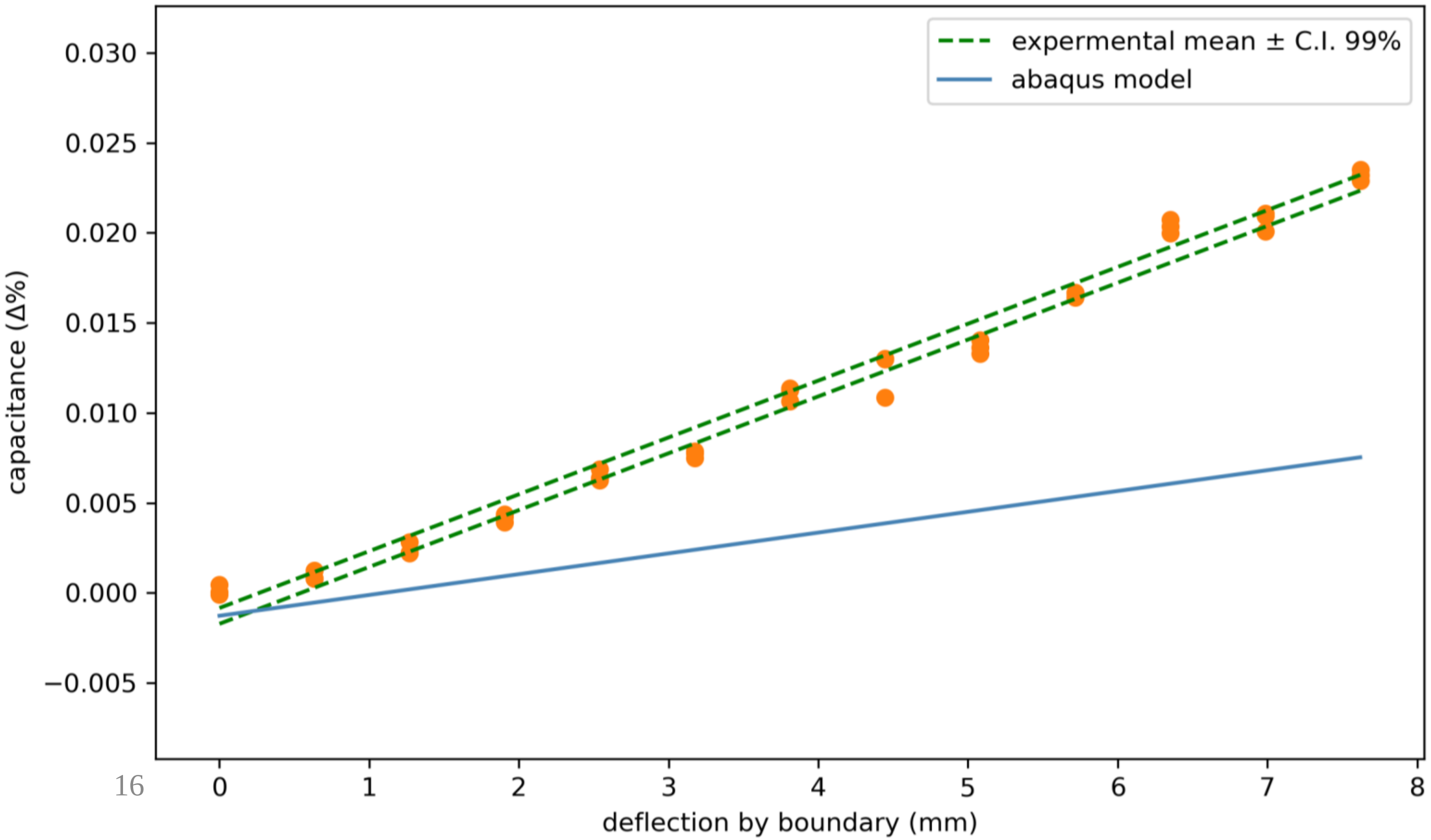
swappable boundary condition

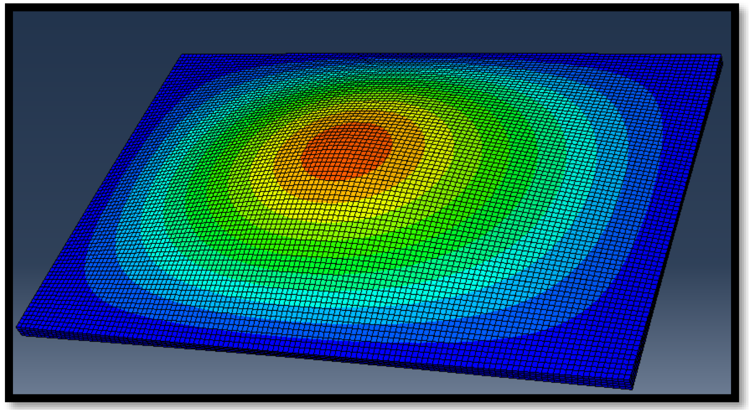


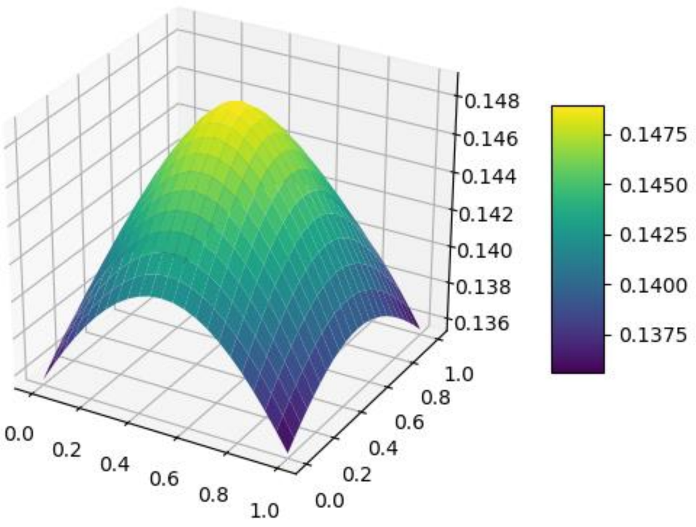
SEC location

SUPPORTING FEA INVESTIGATION

Simply support all edges

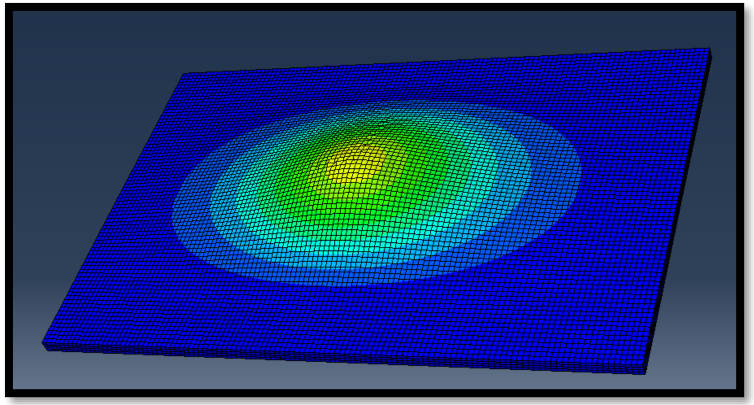


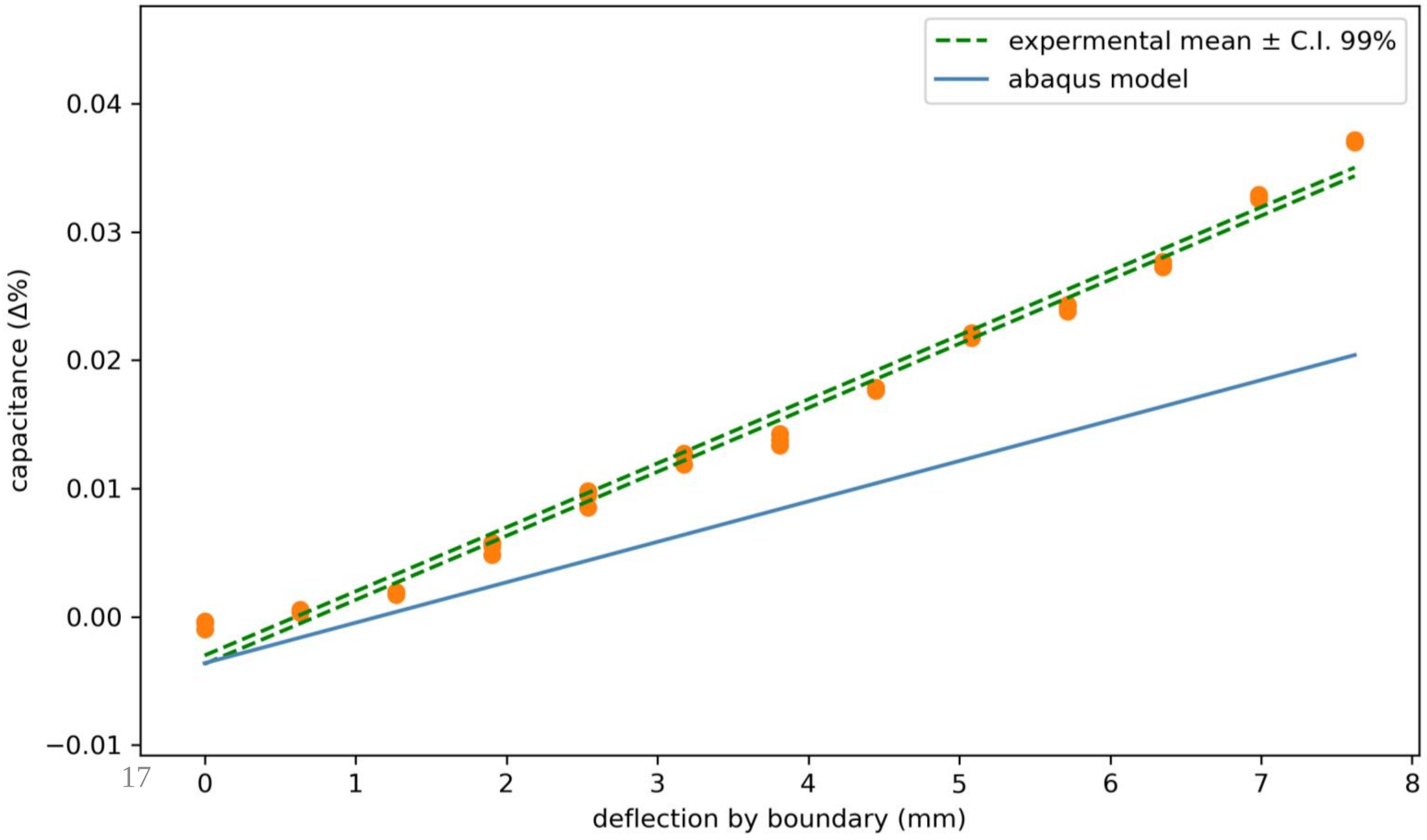


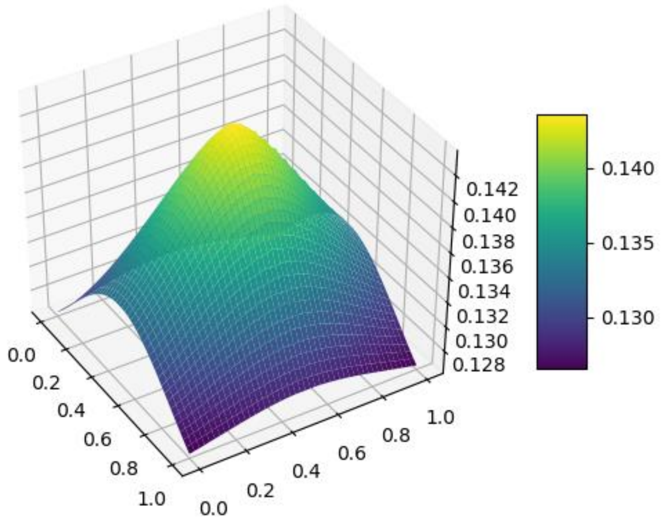


SUPPORTING FEA INVESTIGATION

Fixed support long edges







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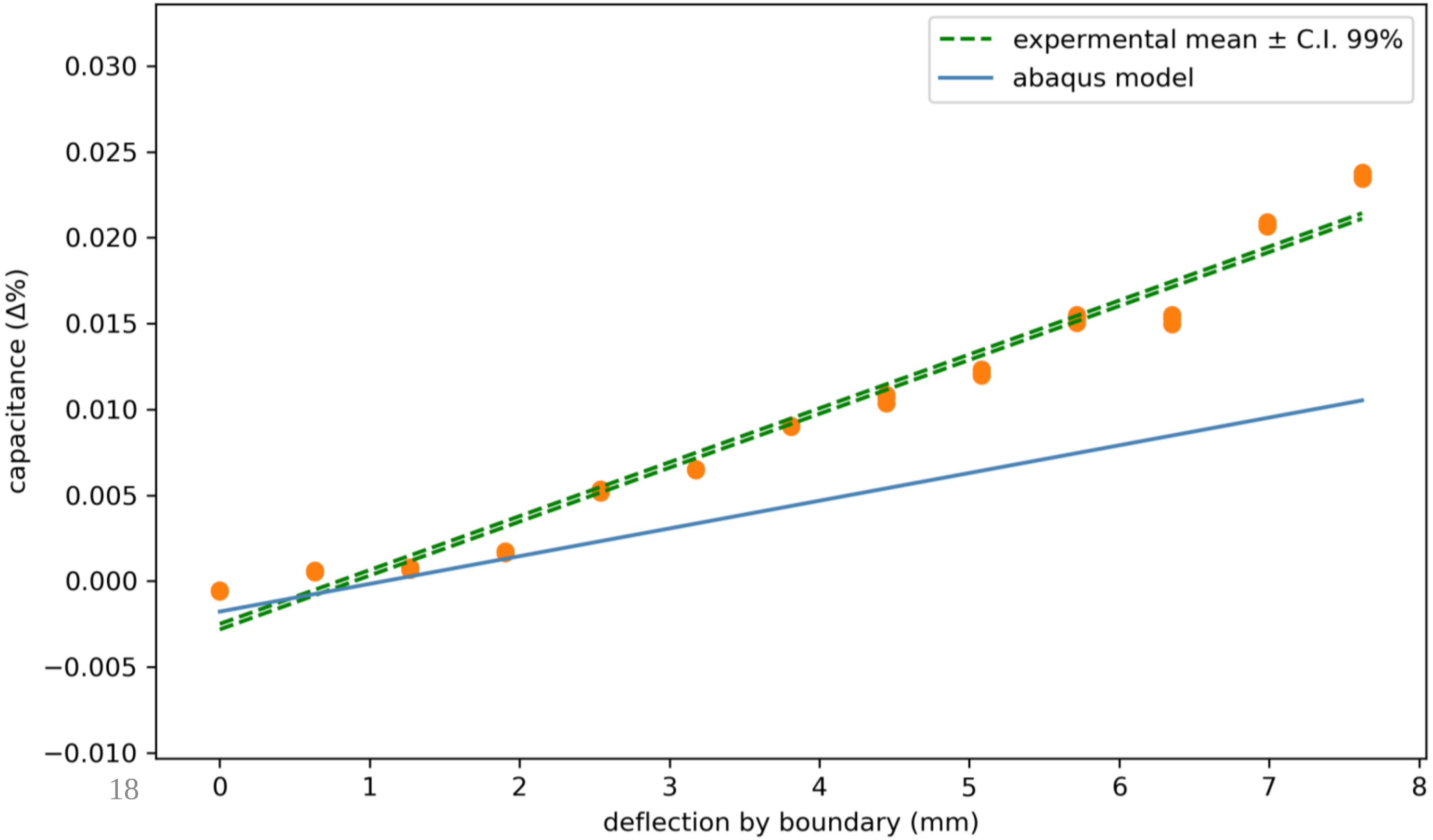
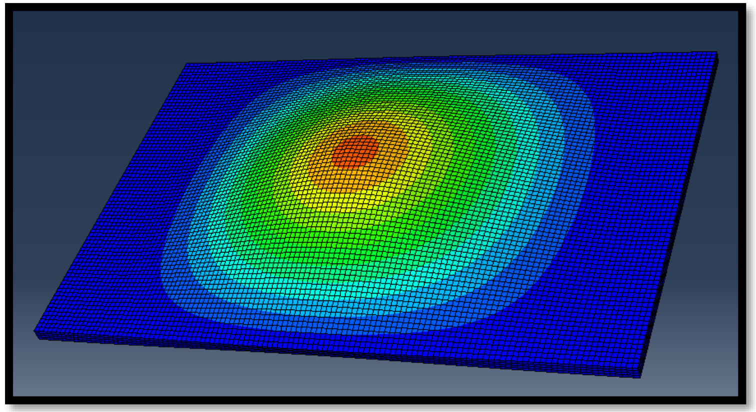
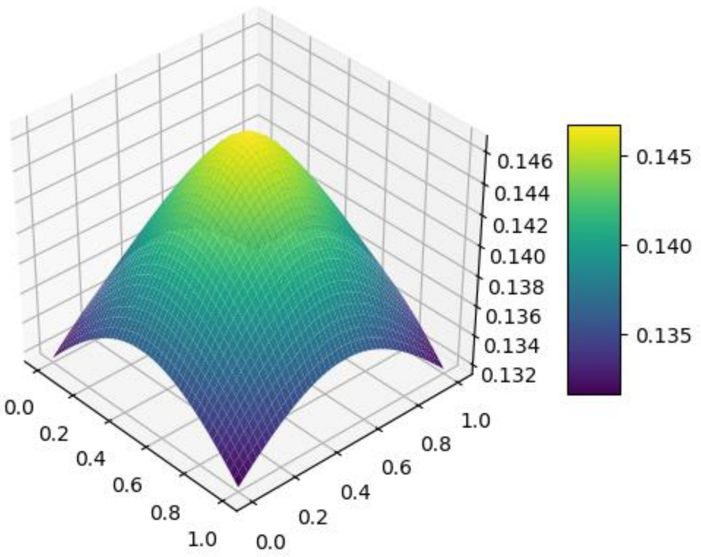
SUPPORTING FEA INVESTIGATION

Fixed support short edges







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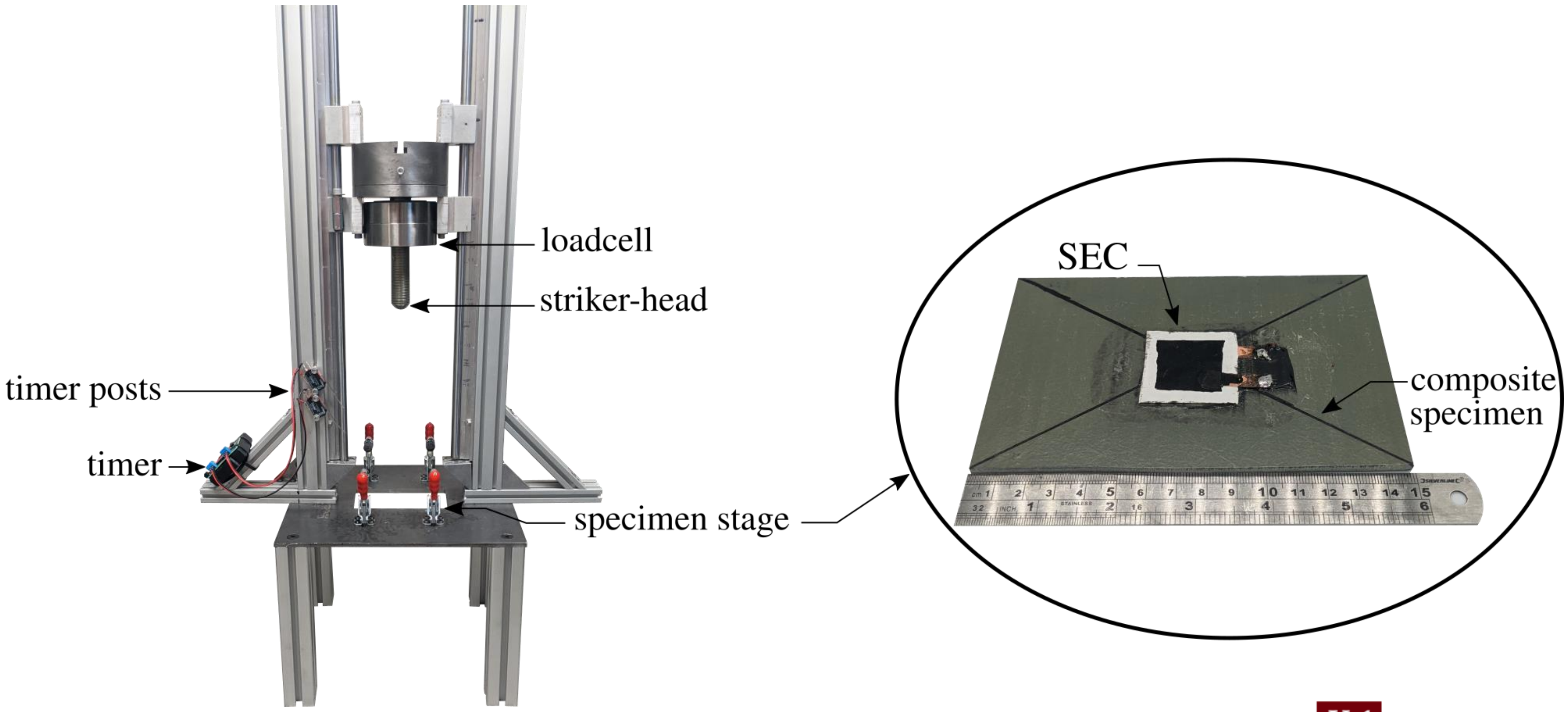
IMPACT STUDY

DROP TOWER



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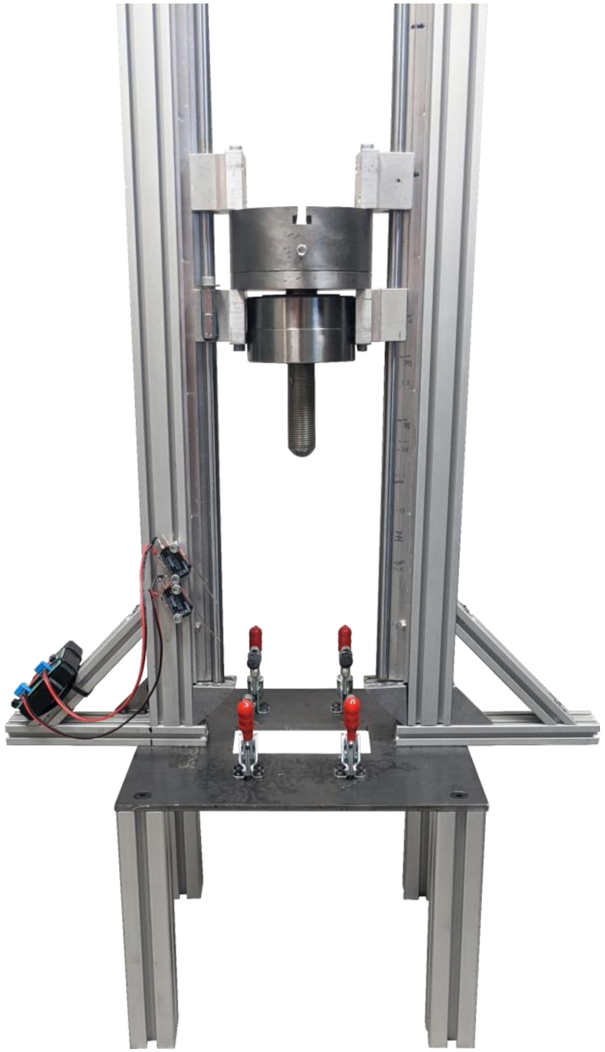
Drop Tower

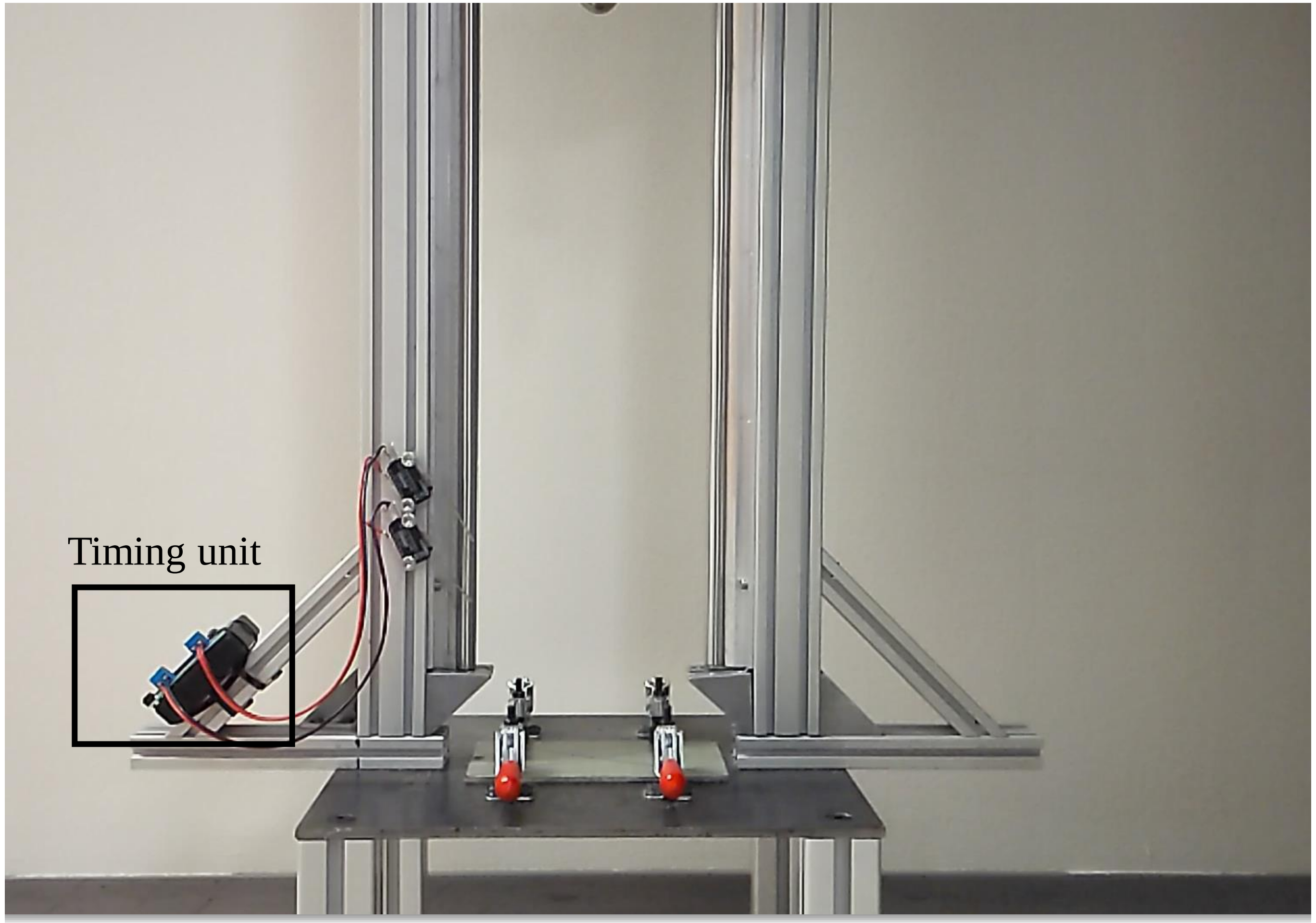
Specifications

- Impactor mass 6.5 kilograms
- Rail length 1 meter
- Maximum energy ≈ 20 joules
- Indenter Hemispherical



Drop Tower

- Timer records in microseconds
  - For average velocity in the 3.5 cm before impact to calculate impact energy
- Impactor caught before second rebound



BACKGROUND

$$E_{\text{sys}} = T_{\text{kinetic}} - U_{\text{potential}} - U_{\text{strain}} = 0$$

Energy balance at time of contact

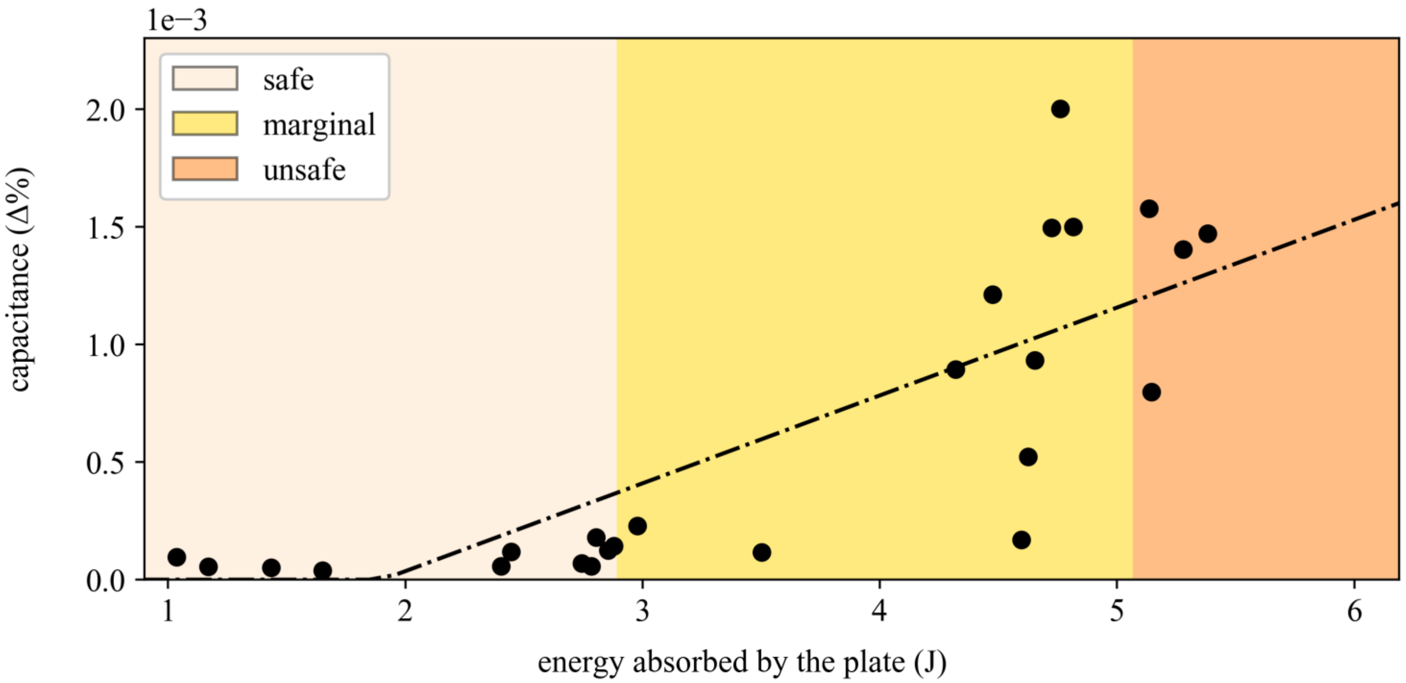
$$\Delta U_{\text{strain}} = \Delta T_{\text{kinetic}} - \Delta U_{\text{potential}}$$

Ignoring frictional losses

$$\Delta U_{\text{strain}} = m\frac{v_{\text{f}}^2 - v_{\text{i}}^2}{2} - \text{mg}\Delta\text{h}$$

Energy remaining in the plate after impact

RESULTS



Nominal proof resilience of GFRP 2.88J to 5.20J

Safe impacts are denoted as the range below the lowest range at 2.88j

Marginal impacts denoted as the range below the range between 2.88j and 5.20J

Unsafe impacts are denoted as the range below the highest range at 5.20J

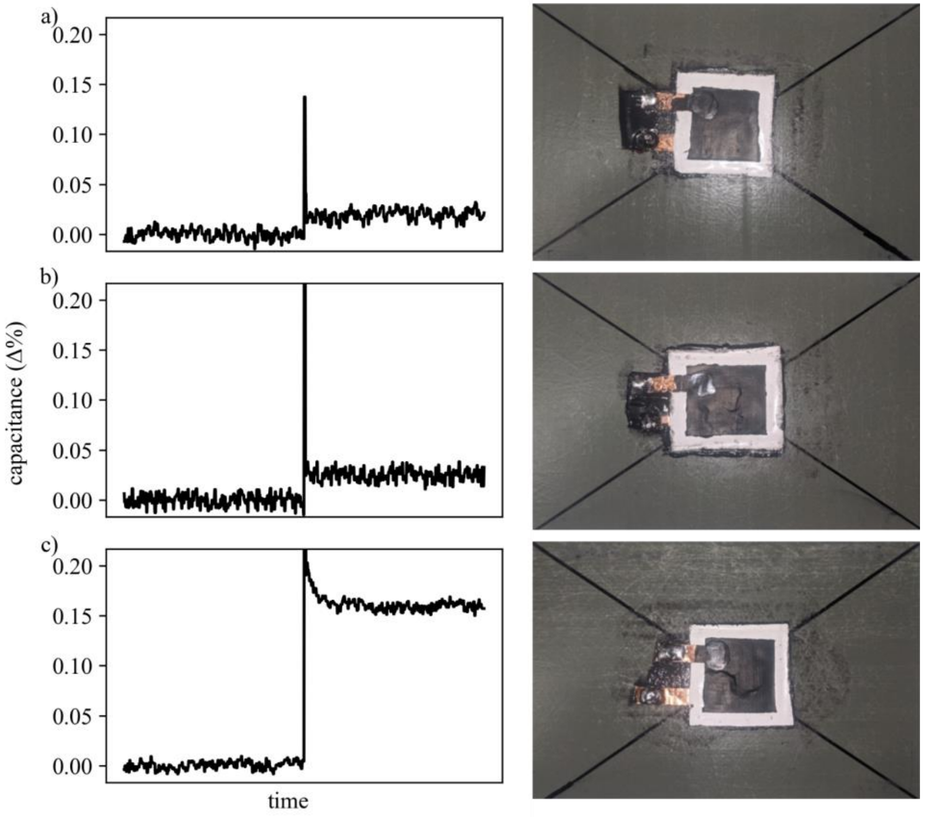
RESULTS

Selected samples from the safe, marginal, and unsafe regions of the distribution

a) a sample in the safe region subjected to a 1.03J impact

b) a sample in marginal region subjected to a 2.84J impact

c) a sample in unsafe region subjected to a 5.14J impact



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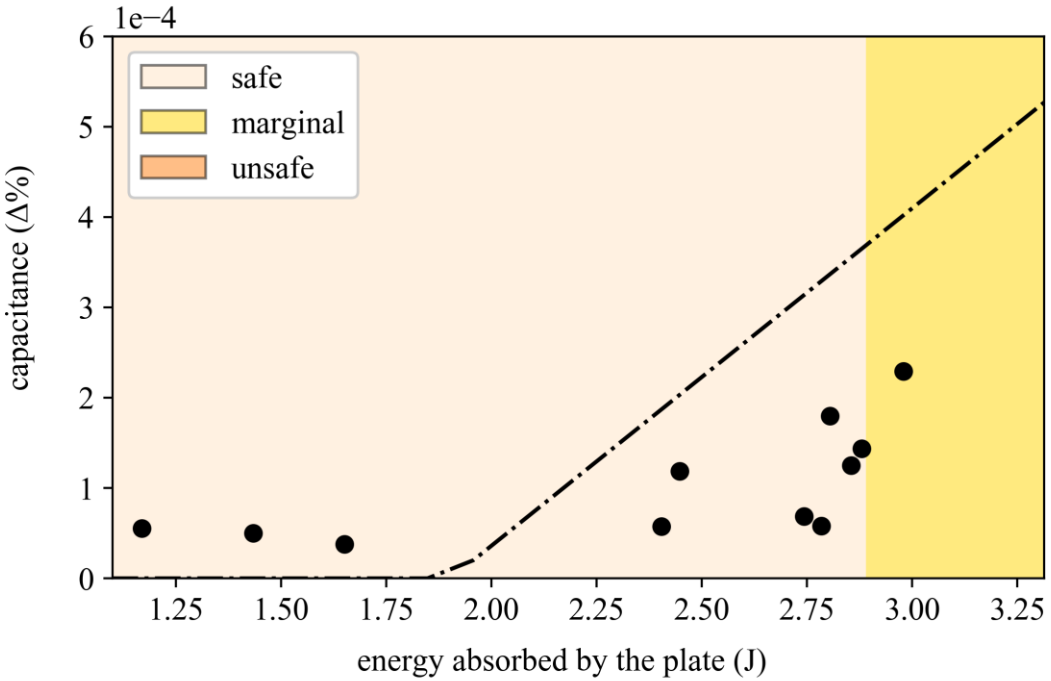
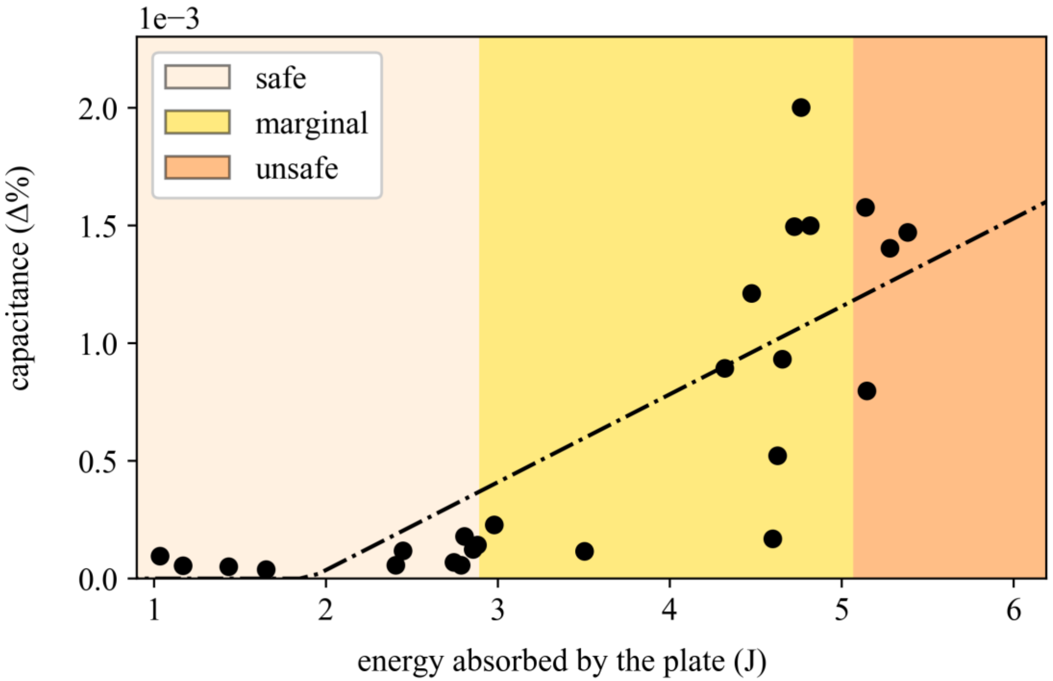
CONCLUSIONS



The trial demonstrated the efficacy of the SEC in determining the failure in the composite plates. The sensors correctly identify failure states in the composite. Registering impacts below the proof resilience. Suggesting a useful perception in barely visible impact detection.

CONCLUSIONS

The sensors benefit from being a large area electronic capable of measuring the entirety of the deformation in the impact. This allows the state assessments to be made about material health. With the robust characteristics of the sensor the material can fully enter and be observed in its failure modes as well.



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THANKS!

Questions: Alexander Vereen

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