# IMPACT MONITORING OF EMBEDDED BATTERIES IN SANDWICH COMPOSITES WITH INTEGRATED SOFT ELASTOMERIC CAPACITORS

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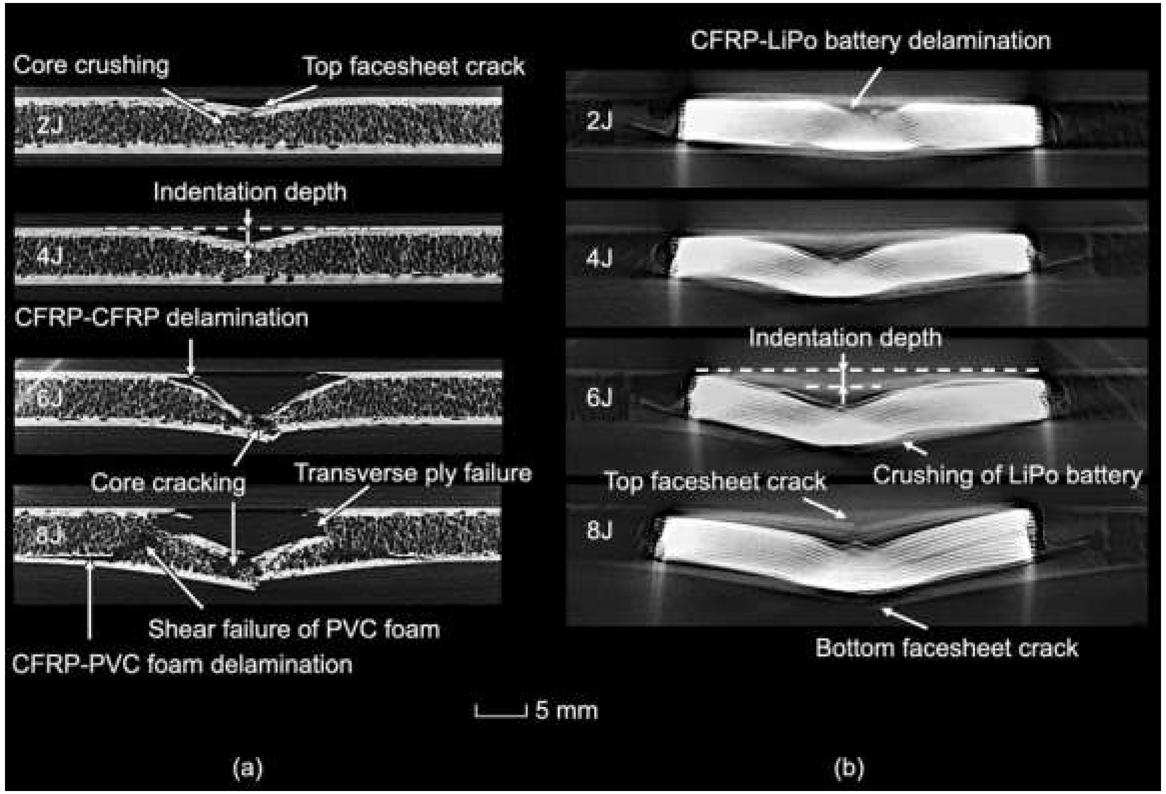
# Embedded Batteries Subjected to Impact

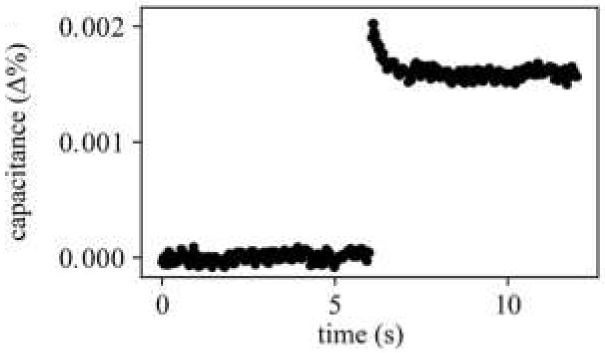
- Embedded batteries alter the energy absorption properties of composites.
- Monitoring impact energy on embedded batteries in composite materials is critical for ensuring the safety and reliability of high-performance applications
- SECs have emerged as a promising solution due to their flexibility, sensitivity, and ease of integration into composite structures

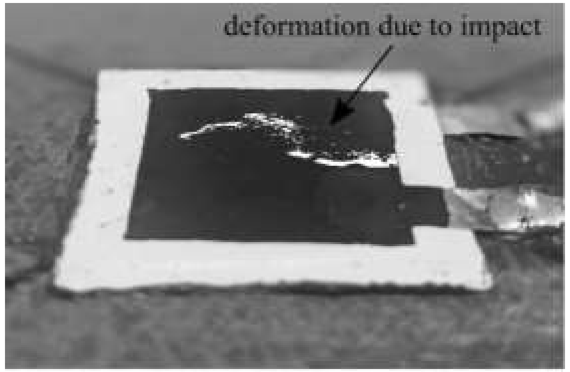


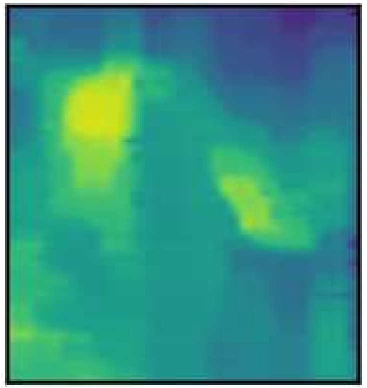

Pattarakunnan, Koranat, et al. "Impact damage tolerance of energy storage composite structures containing lithium-ion polymer batteries." Composite Structures 267 (2021): 113845.

# Large Aera Sensors for Monitoring Impacts

- Prior work on monitoring impact damage in composites using large-area sensors.
- The team has developed a Soft Elastomeric Capacitor (SEC) developed for SHM
- SECs have emerged as a promising solution due to their flexibility, sensitivity, and ease of integration into composite structures



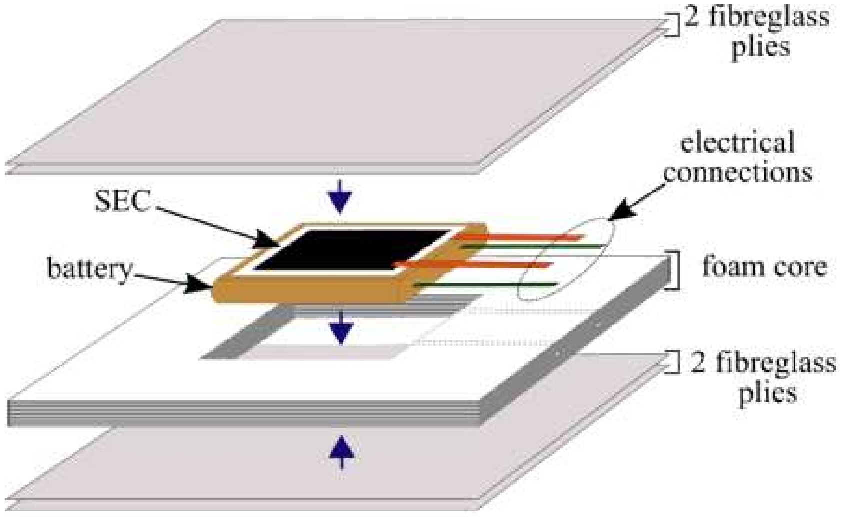



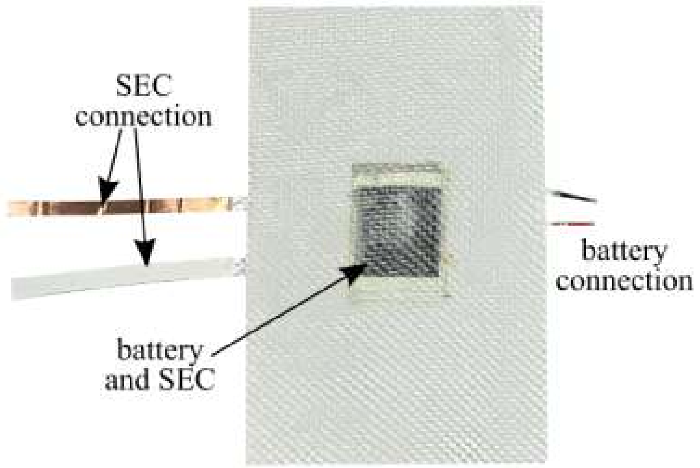



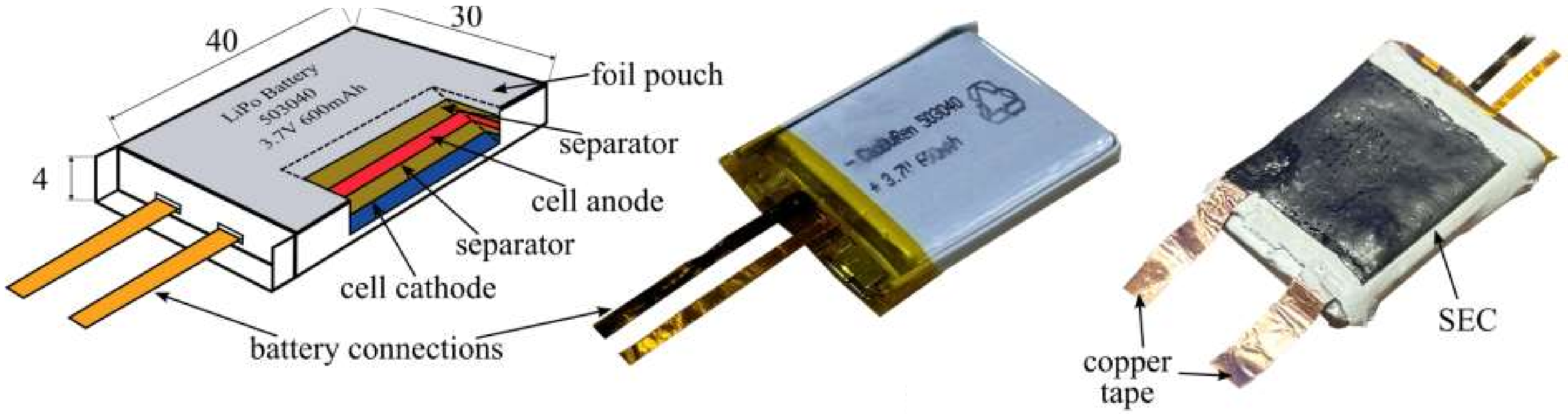
Vereen, A., Downey, A. R., Sockalingam, S., & Laflamme, S. (2023). Validation of large area capacitive sensors for impact damage assessment. *Measurement Science and Technology*, *35*(3), 035106.

# EMBEDDED BATTERIES IN SANDWICH COMPOSITES

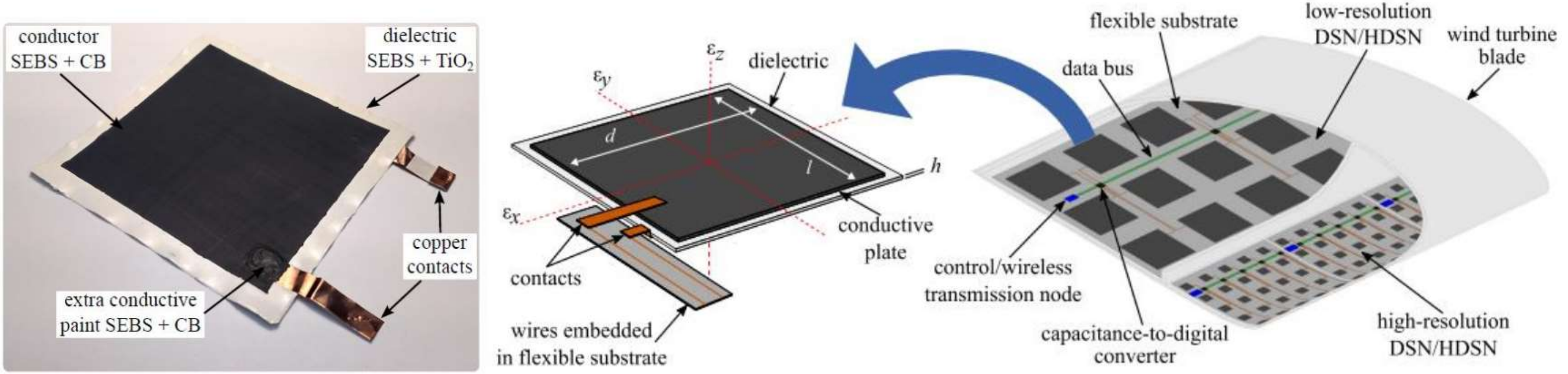
- Embedded batteries into foam core composites.
- Sensors adhered to batteries to measure impact.
- Sensors assist it understanding the effect of impact on structural batteries.



# BACKGROUND



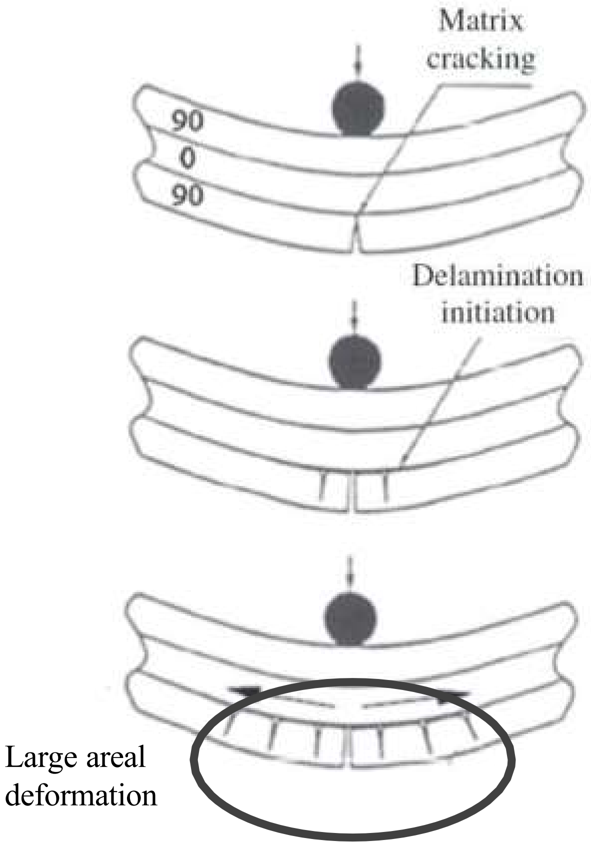

The sensor has the following features:

- 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.*

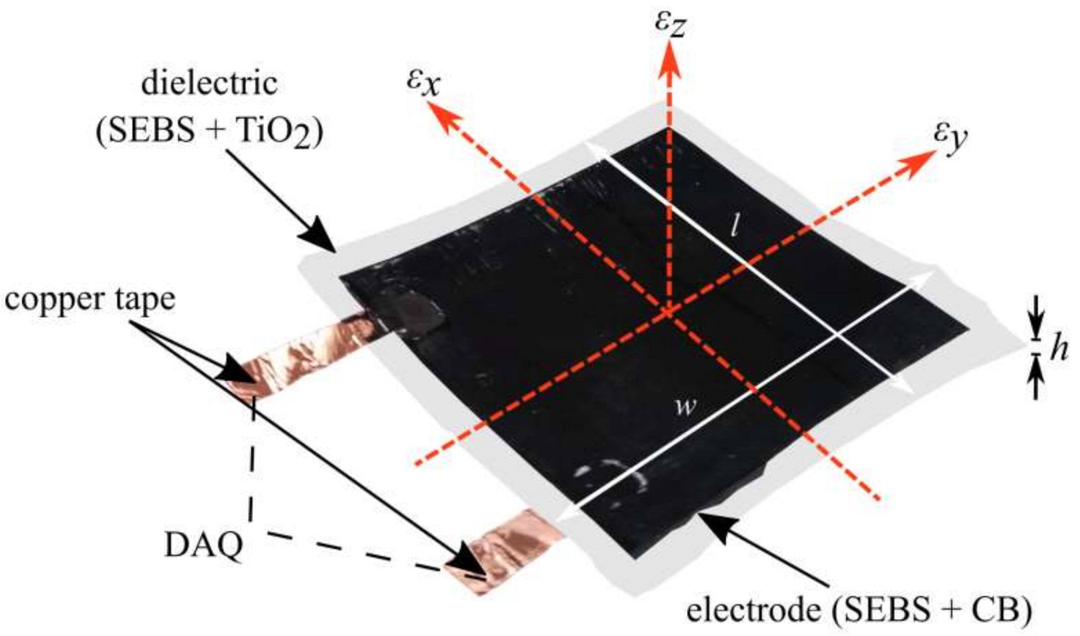
# SOFT ELASTOMERIC CAPACITOR FOR IMPACTS

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

# THE SOFT ELASTOMERIC CAPACITOR : 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

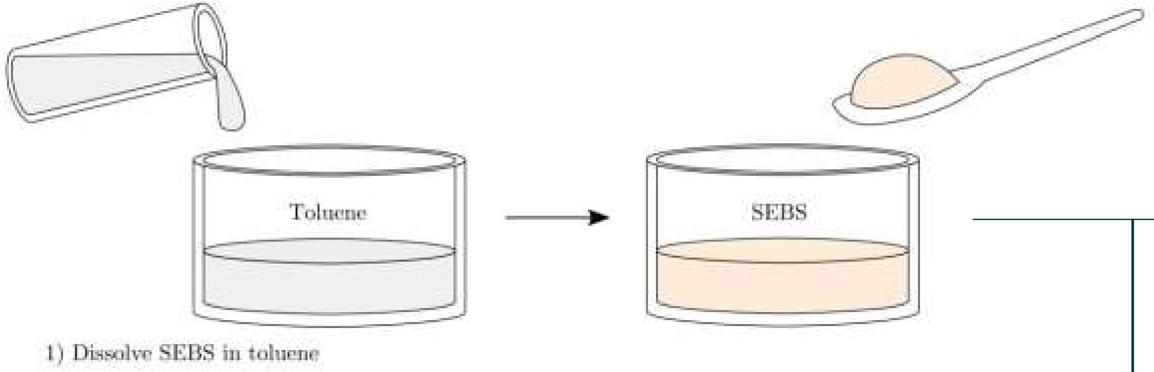
$$\varepsilon_\mathrm{h} = -\frac{\nu}{E}(\sigma_\mathrm{l} + \sigma_\mathrm{w}) = -\frac{\nu}{1-\nu}(\varepsilon_\mathrm{w} + \varepsilon_\mathrm{l})$$

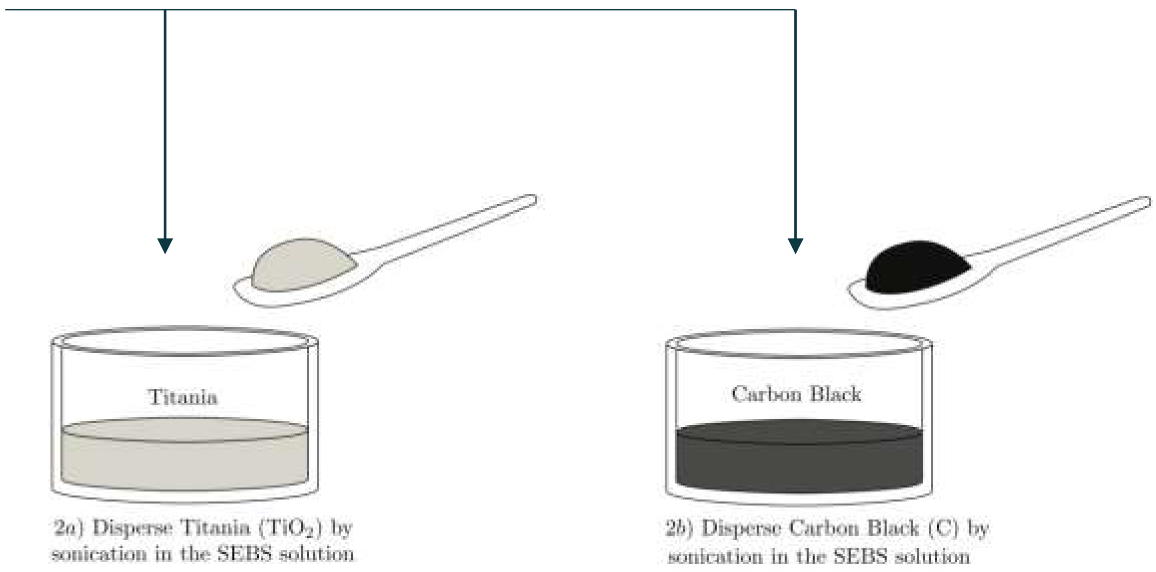
Plane stress assumption

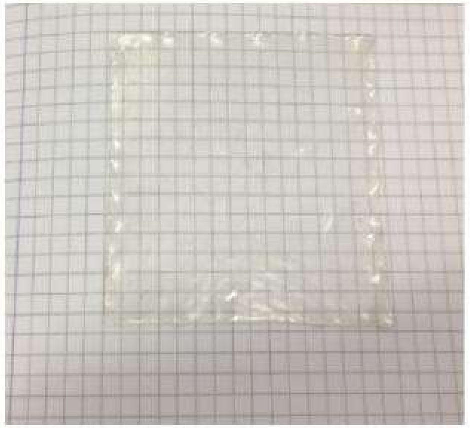
$$\frac{\Delta C}{C_0} = \frac{1}{1-\nu}(\varepsilon_\mathrm{l} + \varepsilon_w)$$

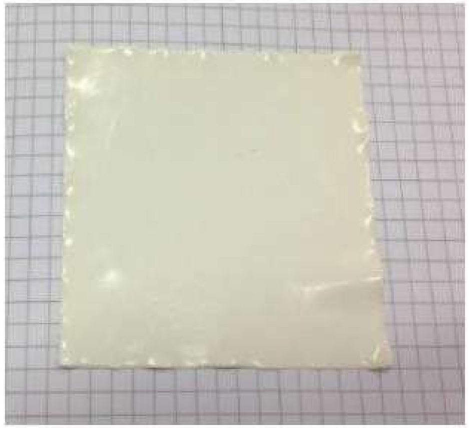
Capacitance in areal deformation

# MANUFACTURE

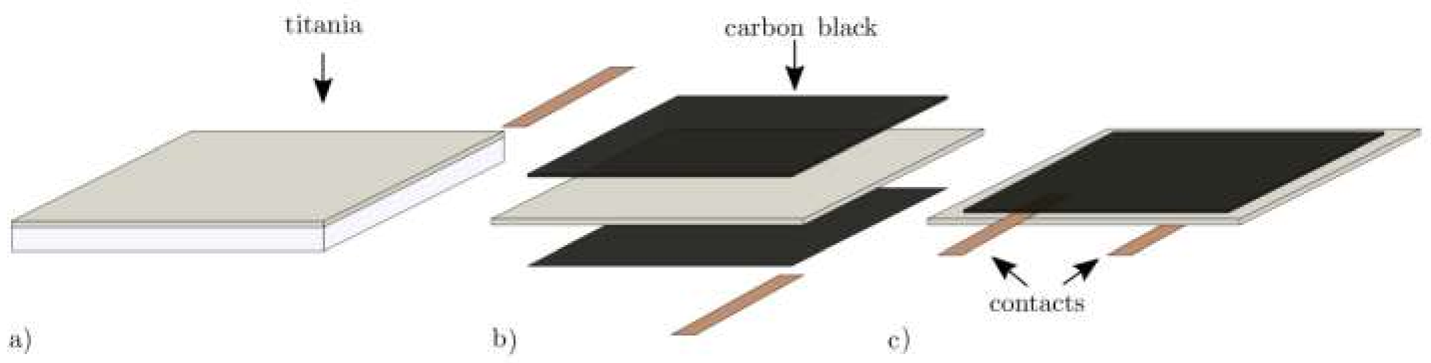




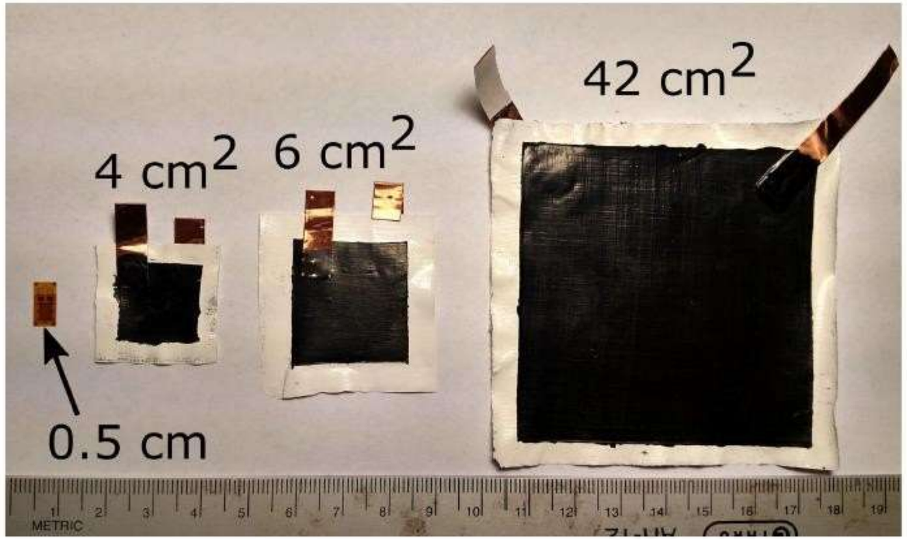
# MANUFACTURE

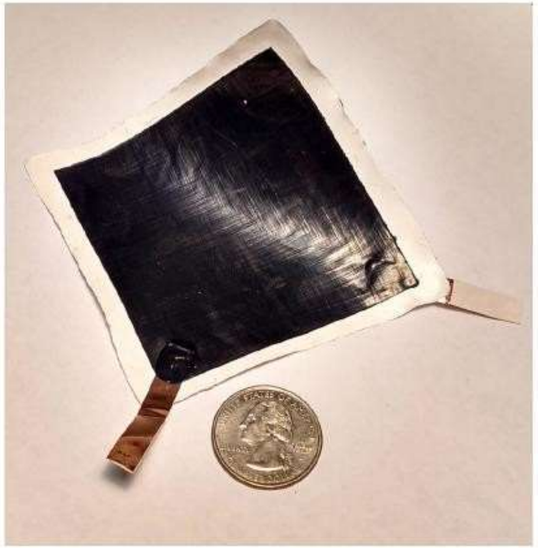



a) The dielectric is drop cast onto a glass pane
b) The carbon black SEBS solution is then painted onto the dielectric in progressive layers
c) Two copper tabs are used for metallic connections to connect to the data acquisition system

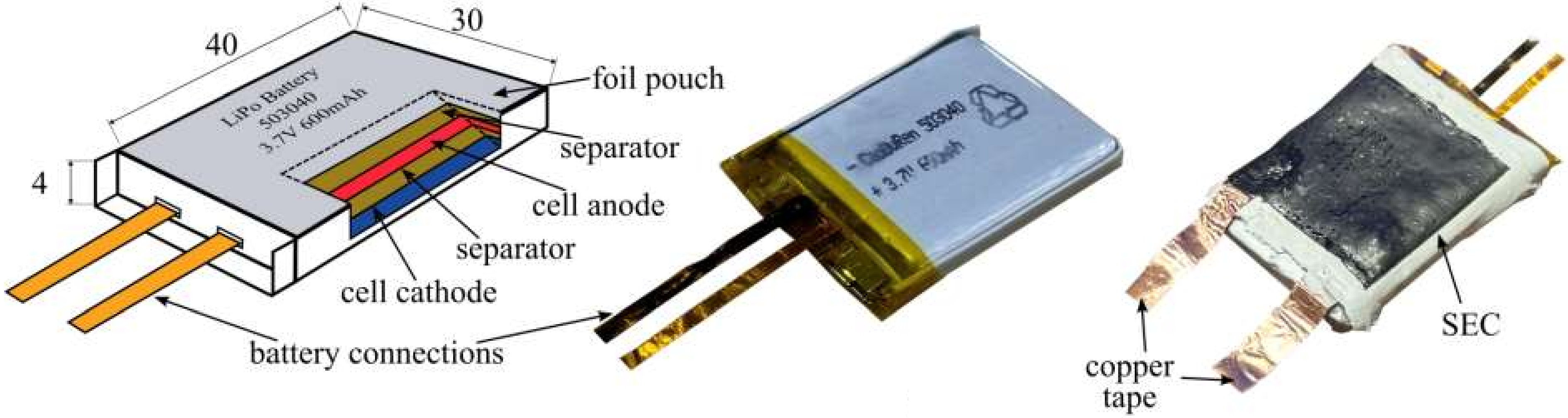
# PROPERTIES

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



# BATTERY SPECIFICATIONS



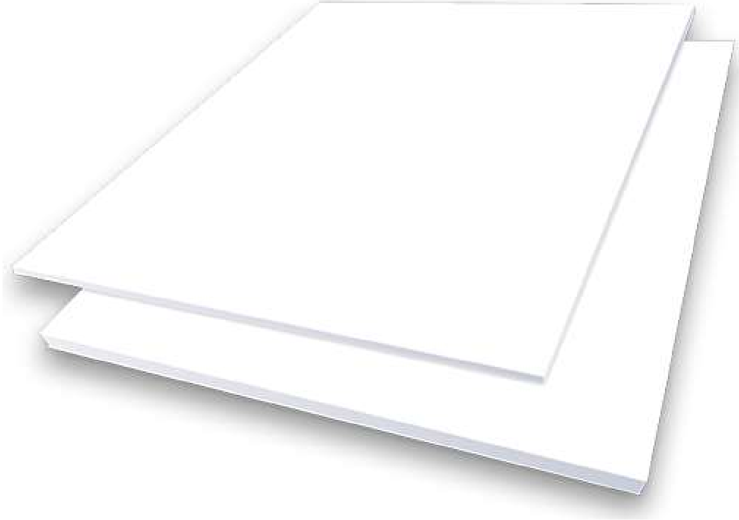

Properties

- Capacity : 600 mAh
- Operating voltage : 3.7 (V),
- Voltage range : 2.7 to 4.2 (V)
- Dimensions : 40 x 30 x 4 mm

# COMPOSITE MANUFACTURING

# COMPOSITE MATERIAL

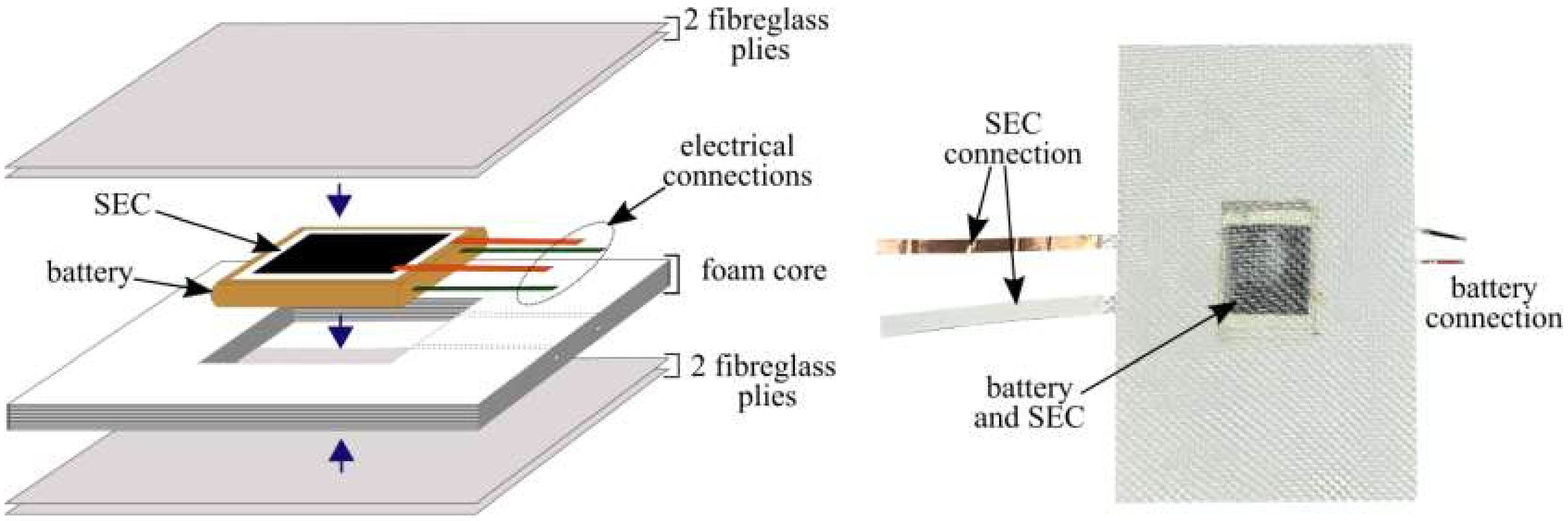
E glass



PVC foam core


Epoxy resin

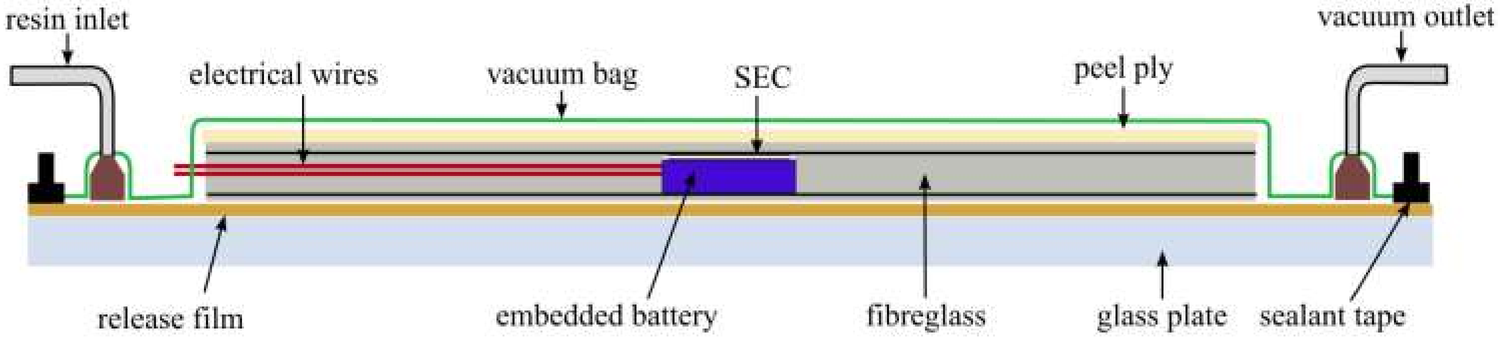
# SANDWICH COMPOSITE



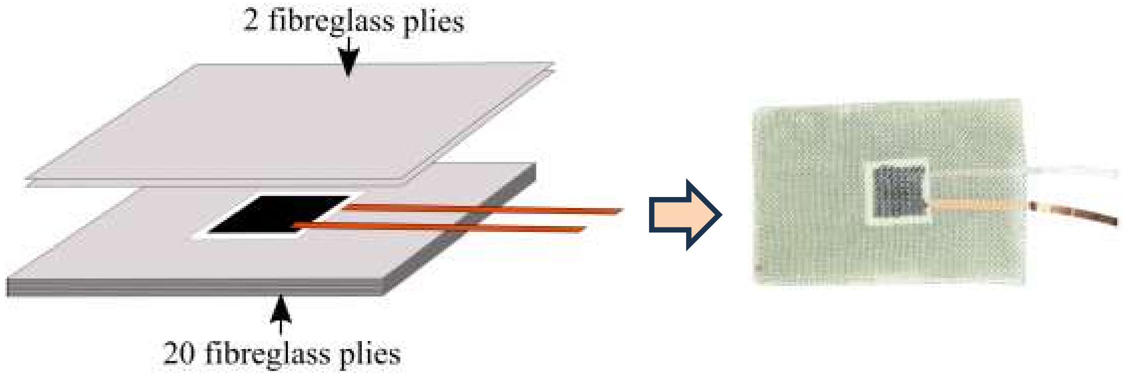

The composite was fabricated using the hand-lay method and allowed to cure for at least 24 hours before any testing.

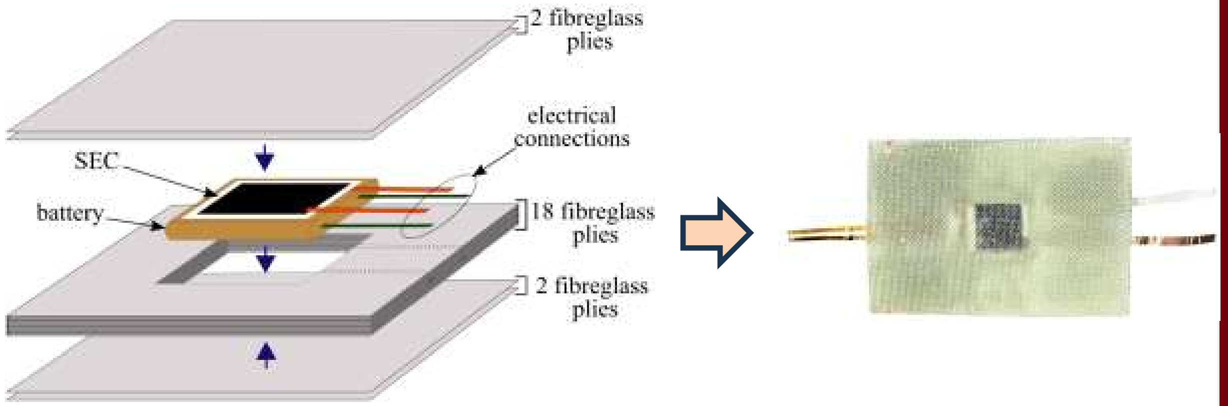
# LAMINATE COMPOSITE

vacuum bag resin infusion (VBRI) technique




Laminate with only embedded SEC



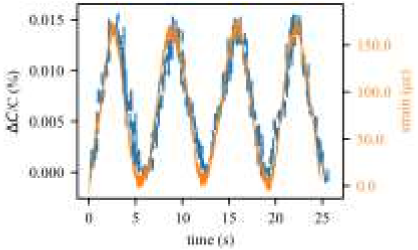




Laminate with embedded SEC and battery

# EXPERIMENTAL VALIDATION

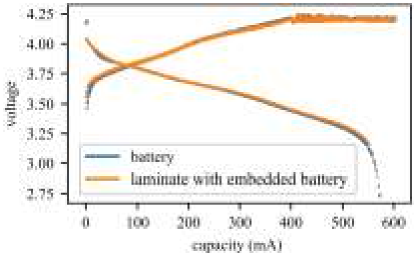
# EXPERIMENTAL PROCEDURE

**TENSILE TEST**



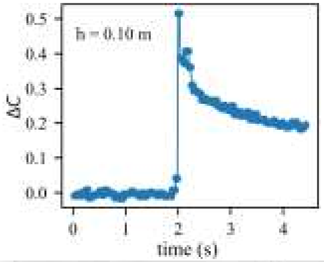

dynamic testing machine

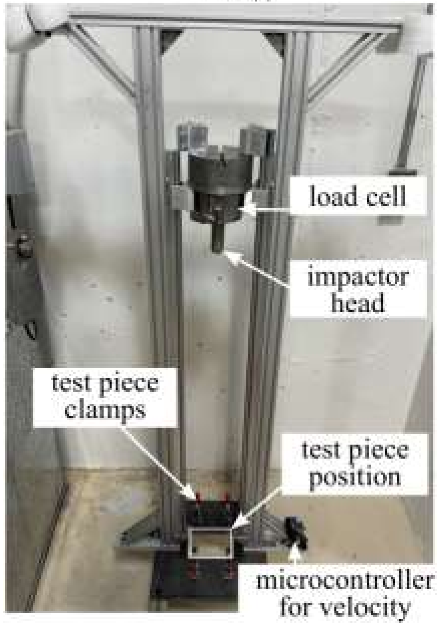
**CHARGE/DISCHARGE TEST**




Charge/discharge station

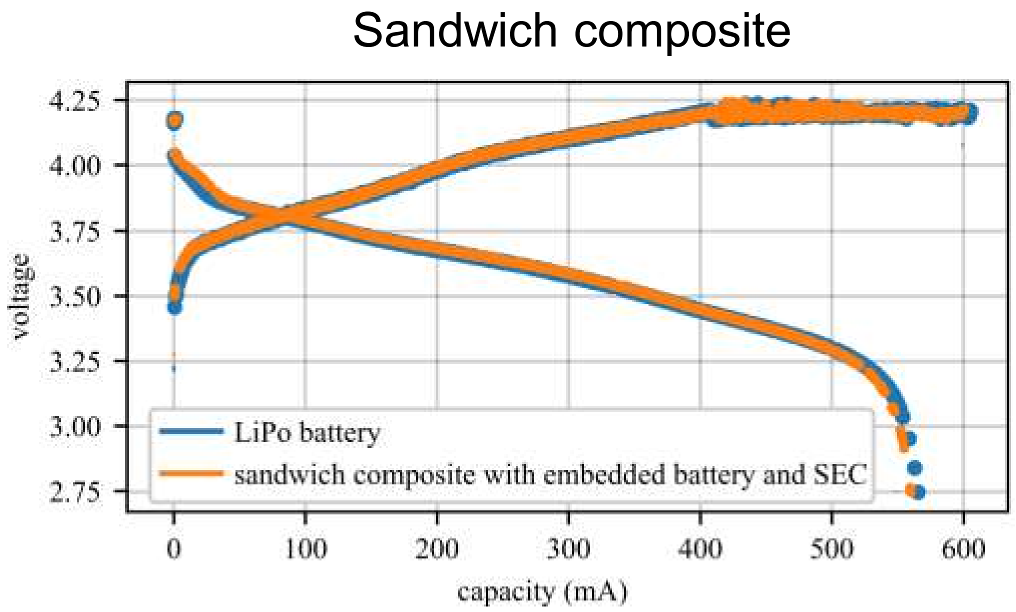
**IMPACT TEST**

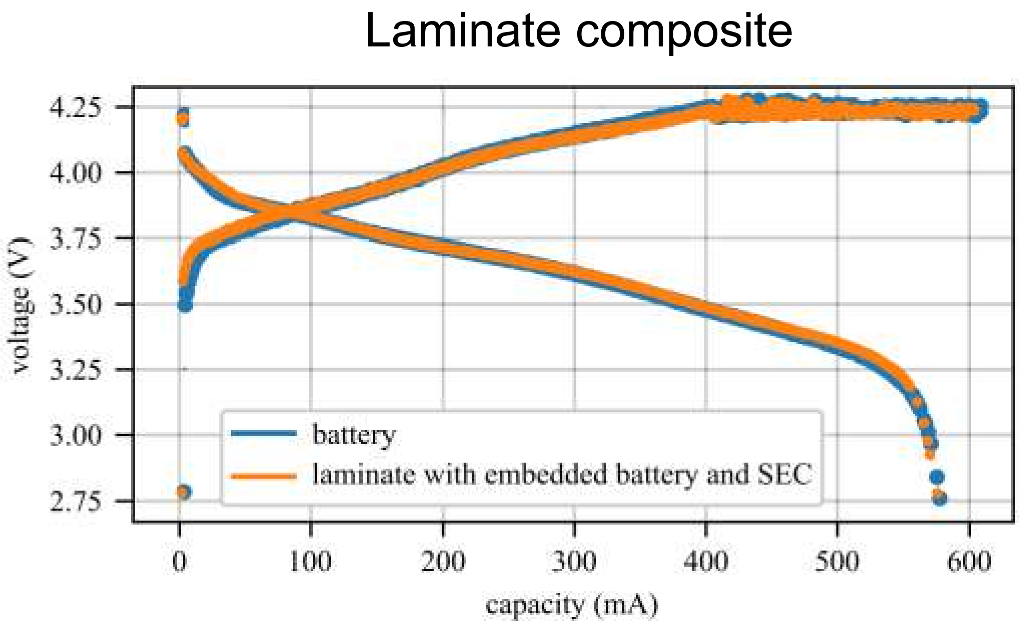



drop weight impact test machine

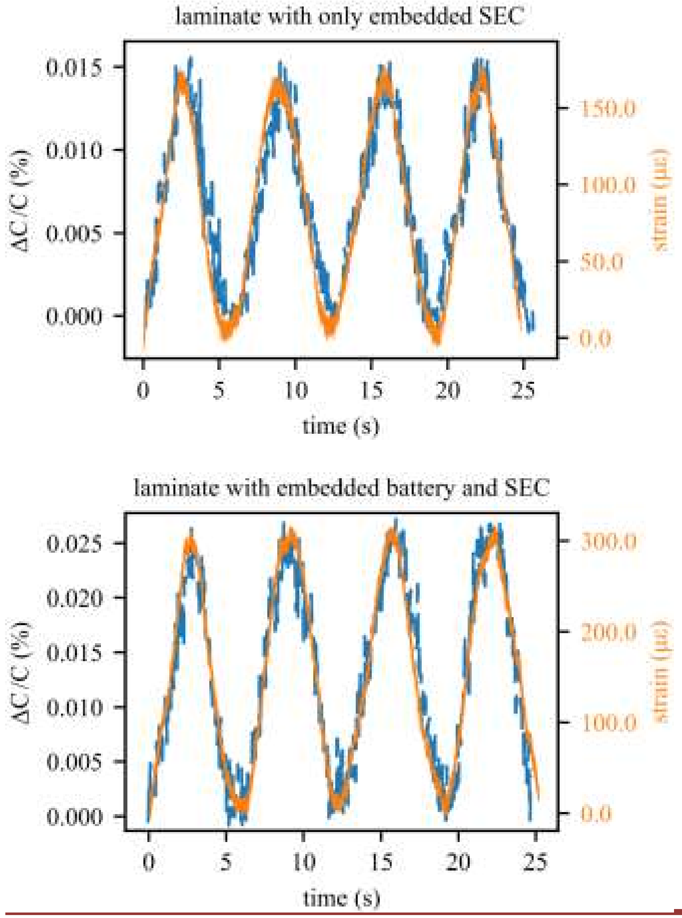
# INITIAL CHARGE/DISCHARGE TEST

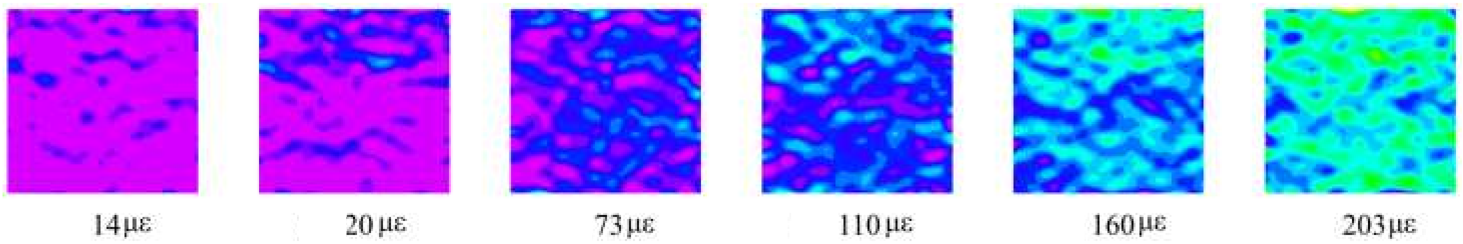


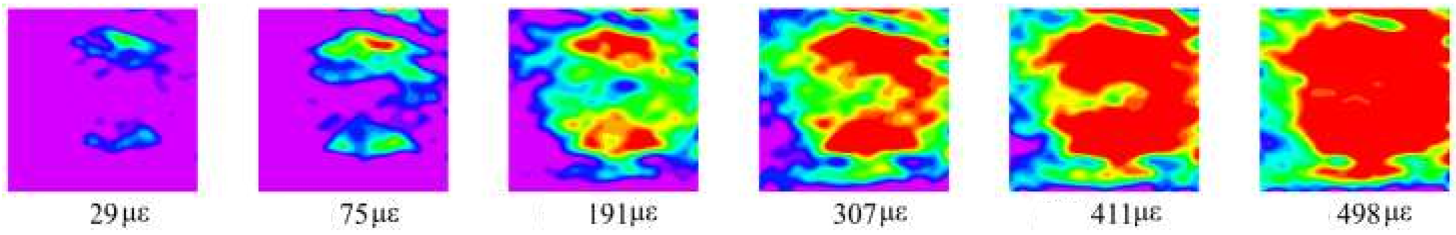
# TENSILE TEST ON LAMINATE COMPOSITE

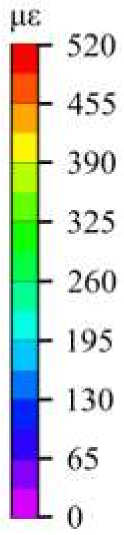
No tensile test was performed on the sandwich composite because of irregular deformation during tensile test



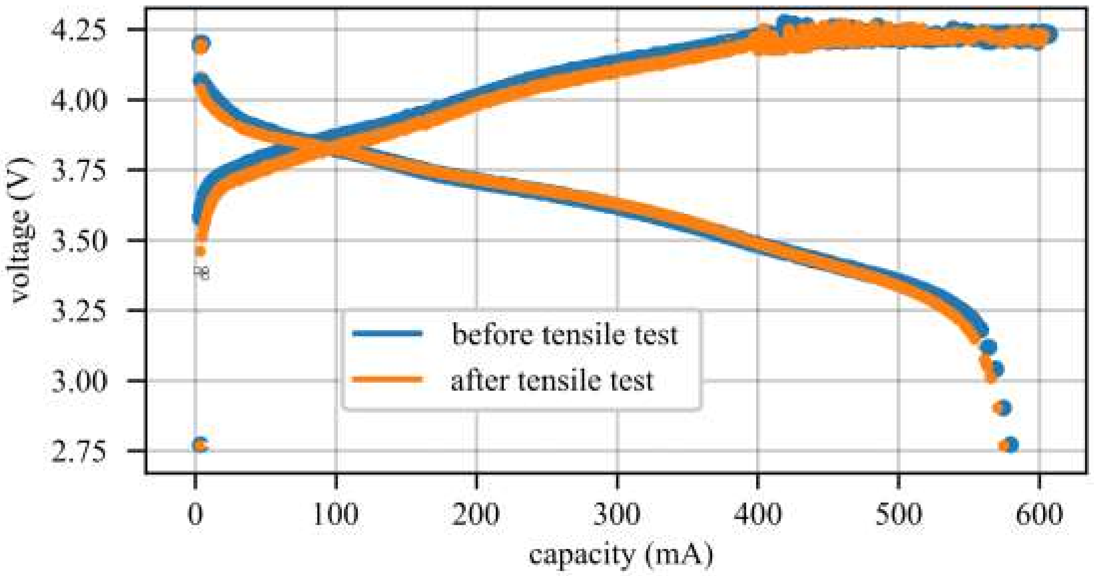




The DIC evaluation shown is for five equal distance points between the lowest strain and highest strain



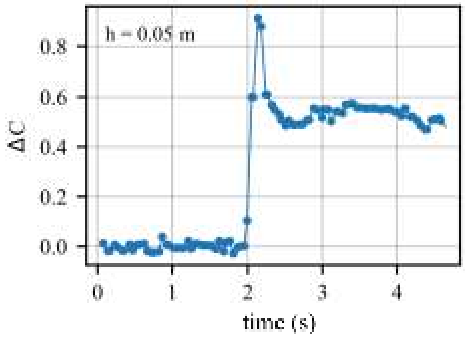
# CHARGE/DISCHARGE TEST ON LAMINATE AFTER TENSILE TEST



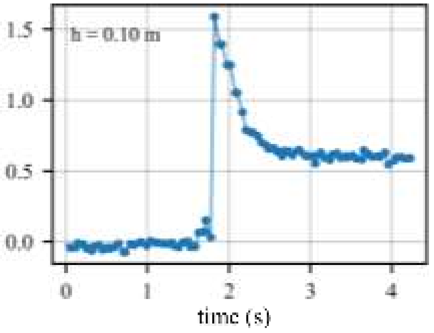

Little change in battery's performance after tensile test showing slight decrease in electrochemical efficiency

# IMPACT TEST : SANDWICH COMPOSITE (ΔC)

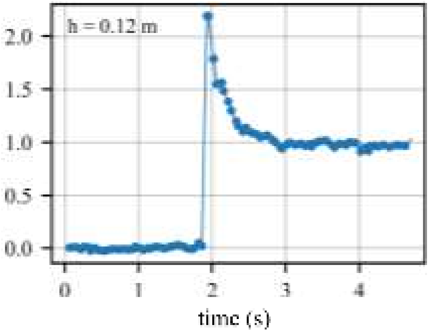
3.86 J



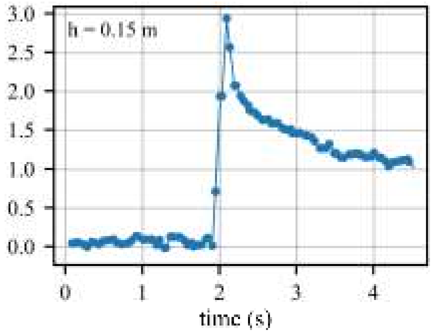

7.36 J



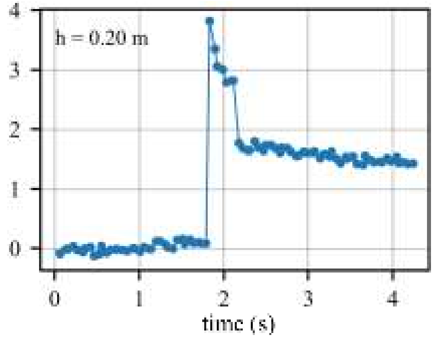

8.83 J




11.04 J



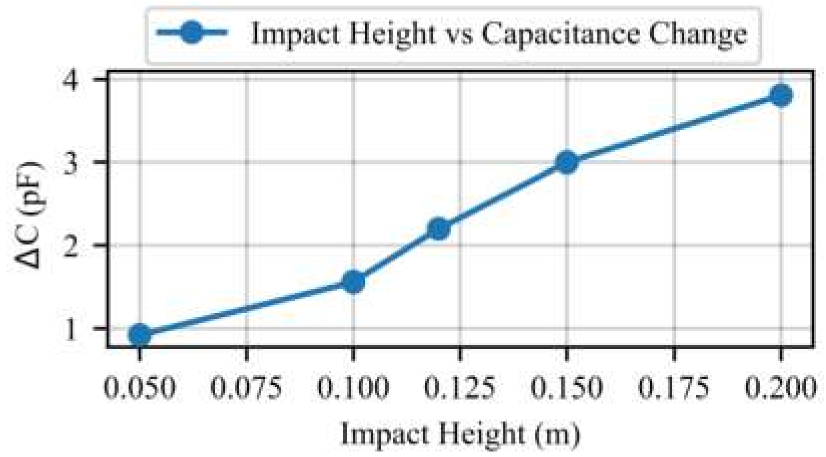

14.72 J

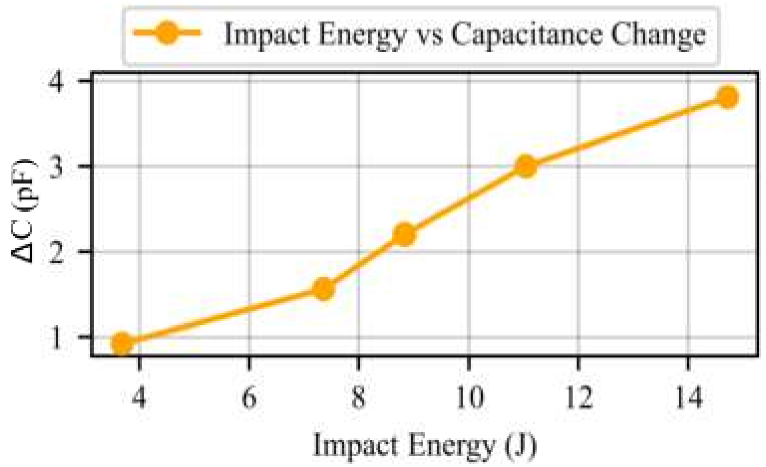



Impact energy and Energy absorbed by the sandwich composite

| Impact Height (m) | Impact energy (J) | $\Delta C$ (pF) | Energy absorbed (J) |
|---|---|---|---|
| 0.05 | 3.68 | 0.92 | 3.35 |
| 0.10 | 7.36 | 1.56 | 6.70 |
| 0.12 | 8.83 | 2.20 | 8.03 |
| 0.15 | 11.04 | 3.00 | 10.04 |
| 0.20 | 14.72 | 3.81 | 13.39 |

# IMPACT ENERGY: SANDWICH COMPOSITE

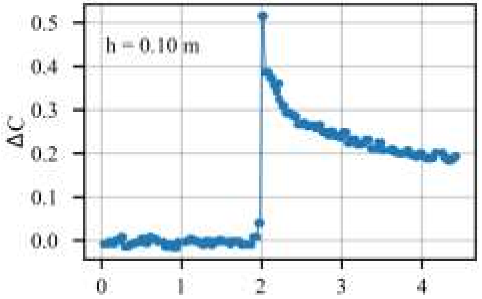


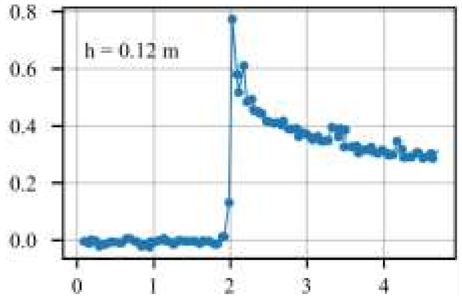
# IMPACT TEST : LAMINATE COMPOSITE ($\Delta C$)

Laminate with only embedded SEC

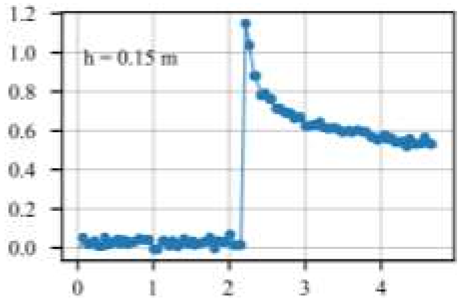
7.36 J



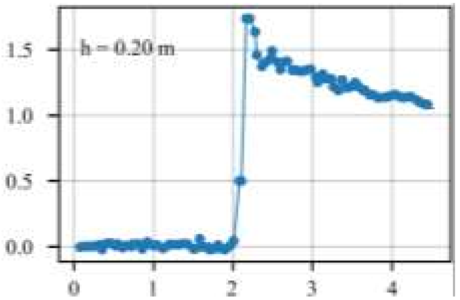

8.83 J



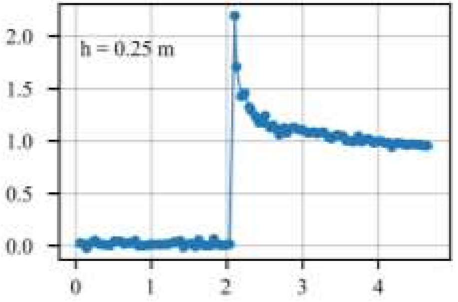

11.04 J




14.72 J

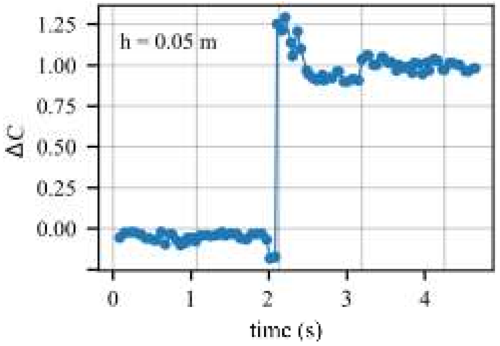



18.34 J

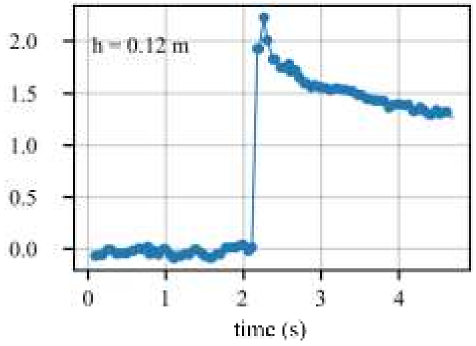



Laminate with embedded SEC and battery

3.86 J




7.36 J

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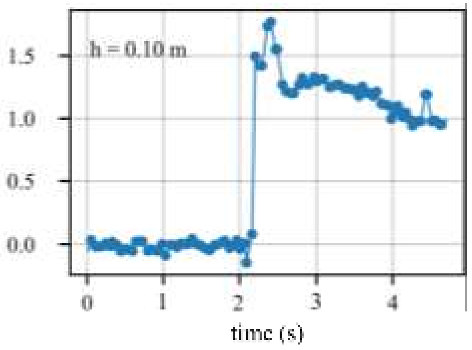


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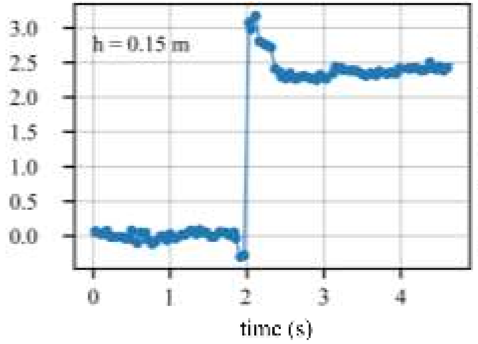


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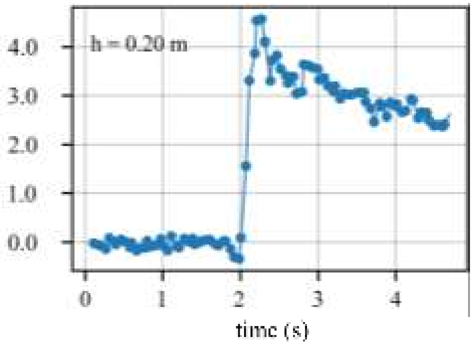
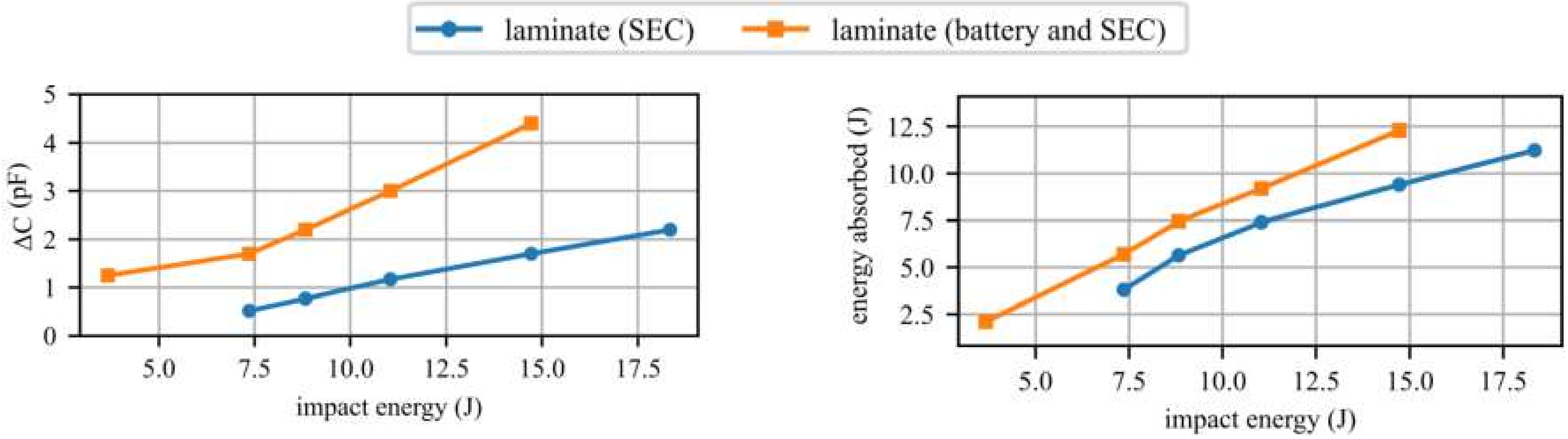


# IMPACT ENERGY : LAMINATE COMPOSITE

Impact energy, capacitance change, and energy absorption of laminates with embedded SEC and battery

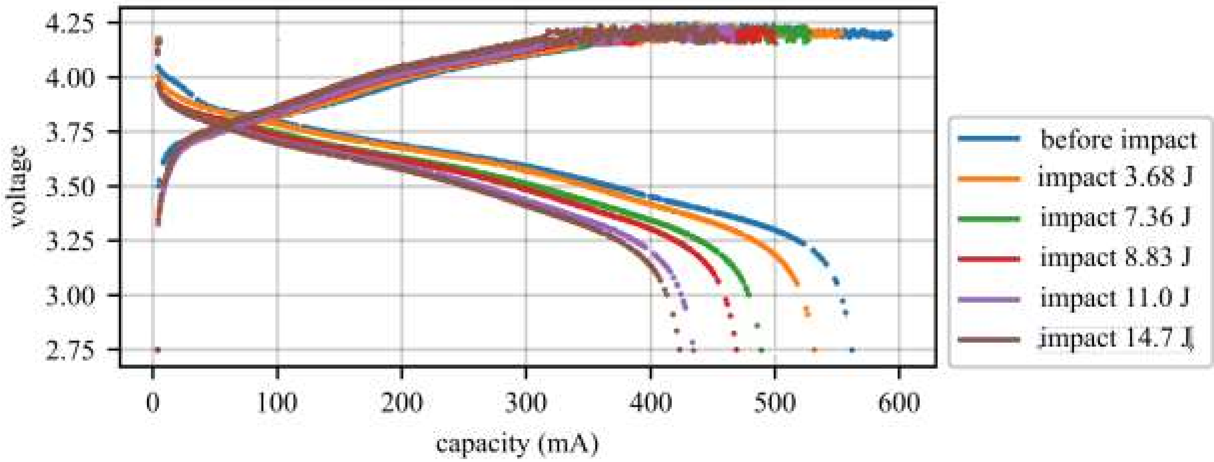
| impact height (m) | impact energy (J) | laminate (sec) | | laminate (battery and SEC) | |
|---|---|---|---|---|---|
| | | $\Delta C$ (pF) | energy absorbed | $\Delta C$ (pF) | energy absorbed |
| 0.05 | 3.68 | - | - | 1.25 | 2.10 |
| 0.10 | 7.36 | 0.52 | 3.80 | 1.70 | 5.70 |
| 0.12 | 8.83 | 0.77 | 6.12 | 2.20 | 7.45 |
| 0.15 | 11.04 | 1.17 | 7.80 | 3.00 | 9.20 |
| 0.20 | 14.72 | 1.70 | 9.40 | 4.40 | 12.30 |
| 0.25 | 18.34 | 2.20 | 11.24 | - | - |

# IMPACT ENERGY : LAMINATE COMPOSITE

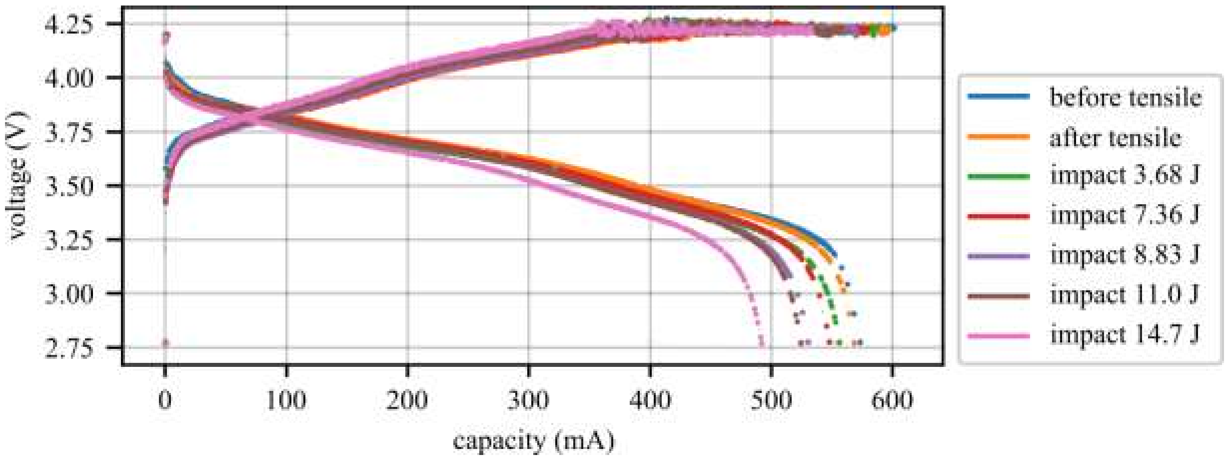


# CHARGE/DISCHARGE TEST AFTER IMPACT

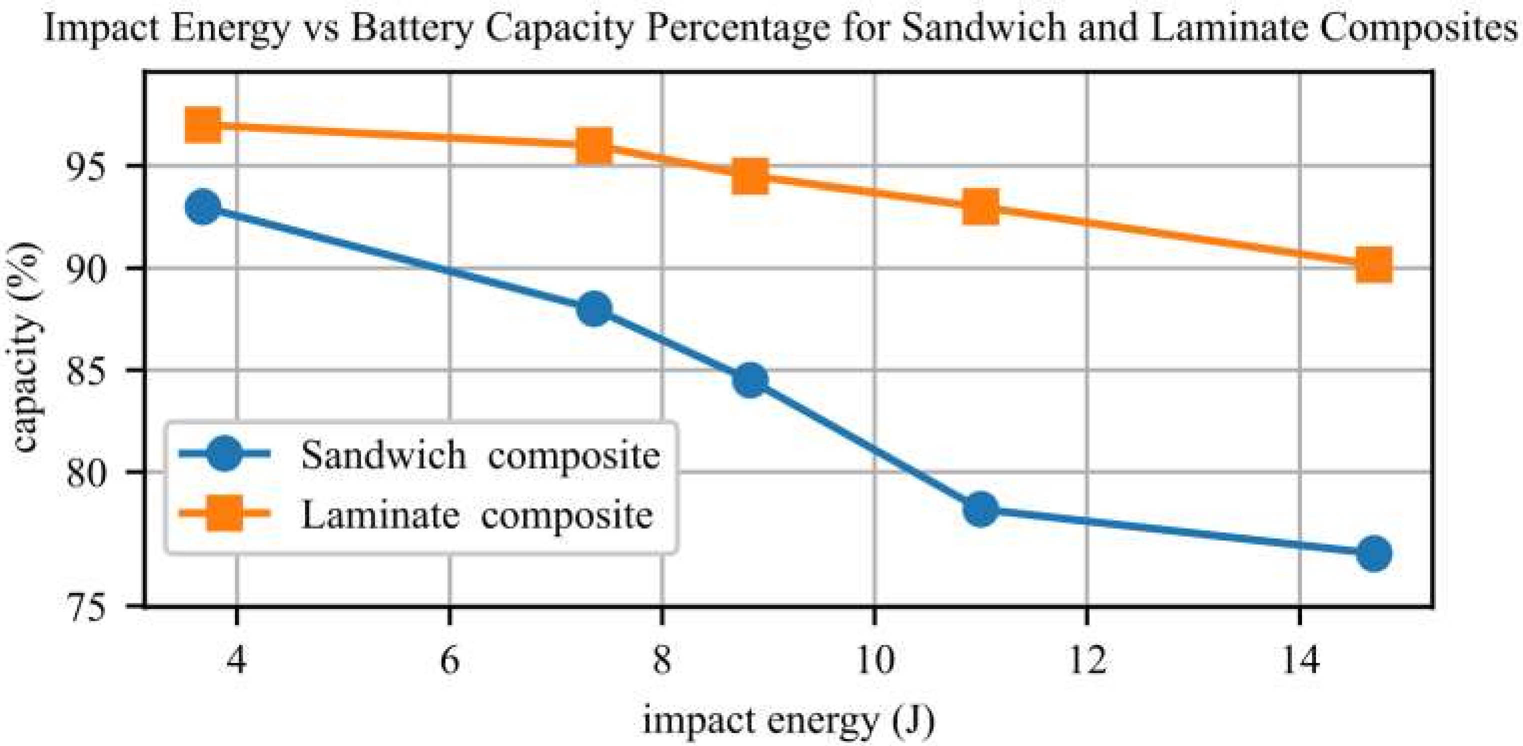
Sandwich composite




Laminate composite



# IMPACT CAUSED BATTERY DEGRADATION



# CONCLUSION

- Embedded batteries alter strain distribution, requiring sensing solutions that conform to complex composite structures.

- SECs reliably correlate capacitance changes with impact energy and maintain functionality post-impact, confirming their effectiveness as embedded sensors.

- Charge-discharge tests revealed performance degradation was in foam core composite structures.

- Performance degradation greater in foam core composite structure.

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