Sensing Skin for In-service Monitoring of Woven Composite Laminates Subjected to Impact Damage

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Department of Mechanical Engineering

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Overview

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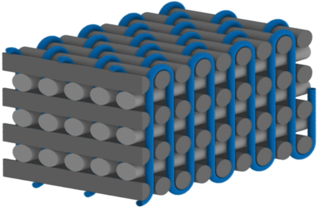


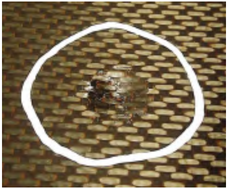
Typical commercial woven composite. textechindustries.com

Objective

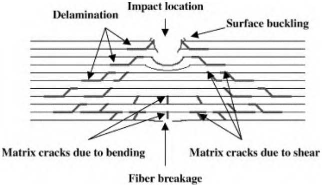
To enable large-area direct impact monitoring in woven composites.

Key considerations:

- Quantify lowest level of detectable damage.
- Provide global coverage of complex shaped structures.
- Localize damage with high spatial resolution.
- Sensing technology needs to be both robust and durable.
- Low-level of ongoing maintenance.
- Easy installation of sensing skin onto structures.



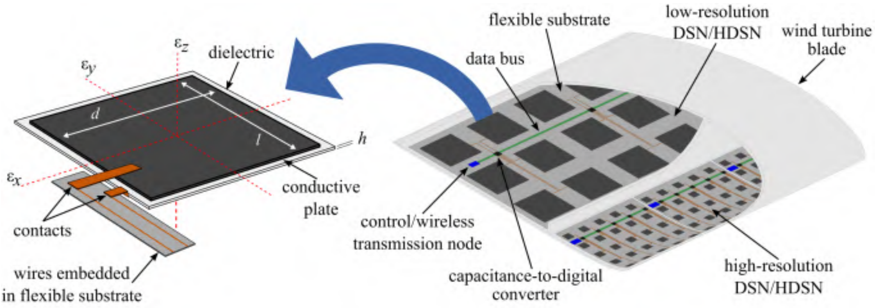
Impact damage in woven composite. compositesworld.com



Damage propagation in a woven composite. dfwptp.com

Fully integrated SEC-based DSN

A fully integrated SEC-based DSN consisting of sensors, data acquisition, and power management all preassembled on a polyimide sheet.



Downey, Laflamme, and Ubertini, “Experimental wind tunnel study of a smart sensing skin for condition evaluation of a wind turbine blade”.

Fully integrated SEC-based DSN

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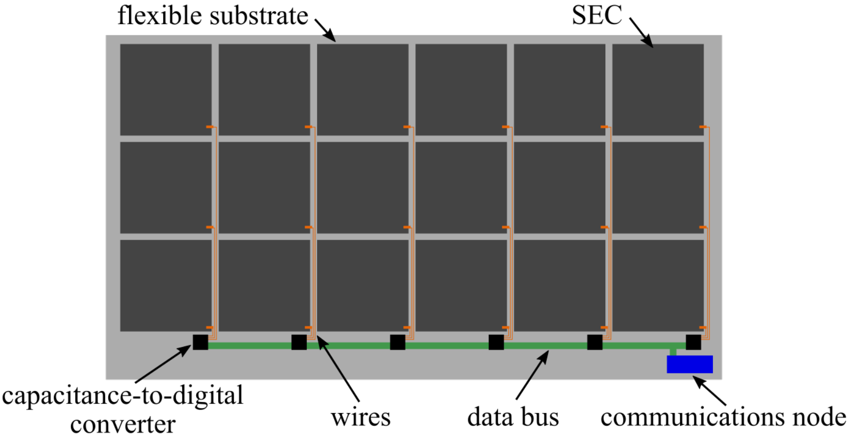
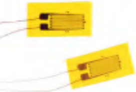


Yan et al., “Surrogate model for condition assessment of structures using a dense sensor network”.

Sensors used for structural health monitoring

Distinguishing the novelty of DSN for mesoscale monitoring.

Sensor type	Inexpensive	Scalable	Simple implementation	Compact data acquisition hardware	Robust	Distinguish local from global damage
Resistive strain gauge (RSG)	x			x		x
Accelerometer (MEMS-based)	x		x	x	x	
Accelerometer (piezoelectric-based)			x		x	
Optical Strain Sensors (FBG)		x				x
Linear variable differential transformer (LVDT)	x		x			
Digital image correlation (DIC)		x				x
Dense sensor networks (DSN)	x	x	x	x	x	x



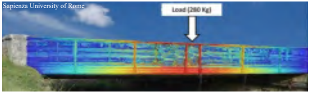
resistive strain gauge

accelerometer (MEMS-based)

accelerometer (piezoelectric-based)

linear variable differential transformer (LVDT)

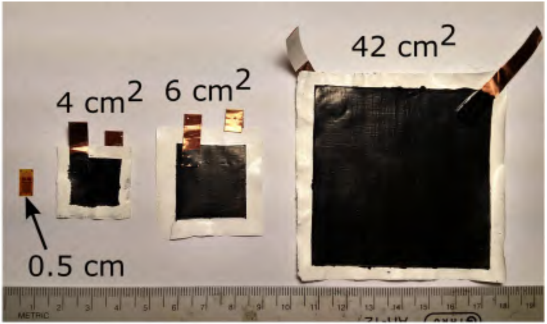
optical Strain Sensors



digital image correlation (DIC)

Soft elastomeric capacitor (SEC)

Large area electronics consisting of a strain-sensitive Soft Elastomeric Capacitor (SEC).



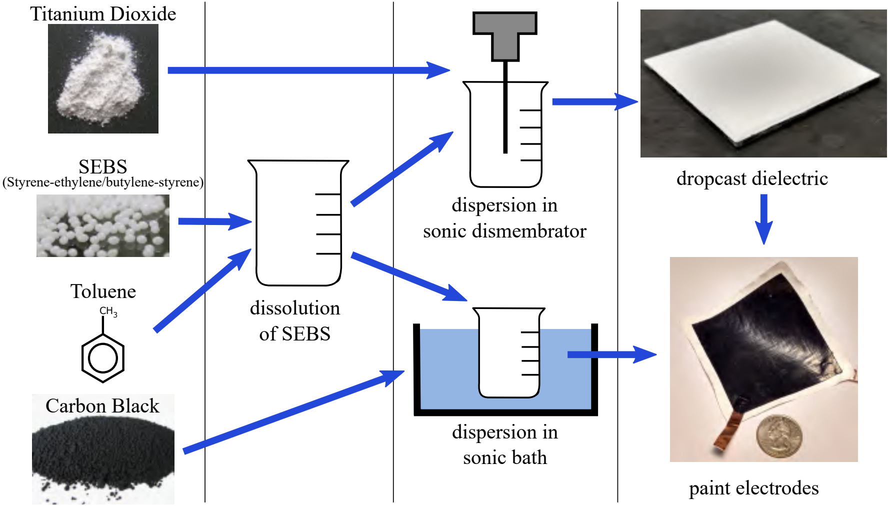
SECs of varying size compared to a resistive strain gauge (RSG).

Highly elastic sensing membrane.

Laflamme et al., “Robust Flexible Capacitive Surface Sensor for Structural Health Monitoring Applications”.

Manufacturing the SEC

Fabrication process of the soft elastomeric capacitor.



Laflamme et al., "Soft Elastomeric Capacitor Network for Strain Sensing Over Large Surfaces".

SEC's electromechanical model

Electromechanical model for the SEC.

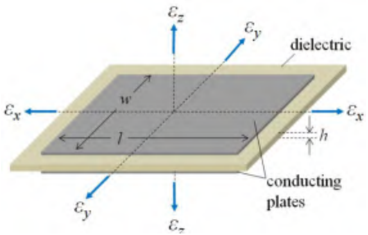
Parallel plate capacitor

$$\Delta C = \epsilon_r \epsilon_0 \frac{\Delta A}{\Delta h}$$

ϵ_r is the relative static permittivity and ϵ_0 is the dielectric constant. Using hooks law;

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

where ε_x is the strain in the x direction, ε_y is the strain in the y direction and λ is the sec's gauge factor ≈ 2 for mechanical excitation under < 15 hz.



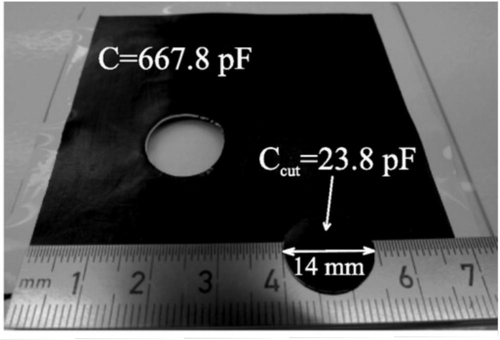
SEC sensor

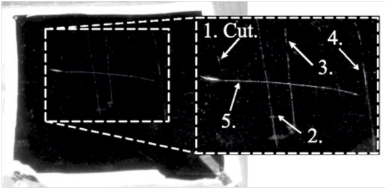
Laflamme et al., "Dynamic Characterization of a Soft Elastomeric Capacitor for Structural Health Monitoring".

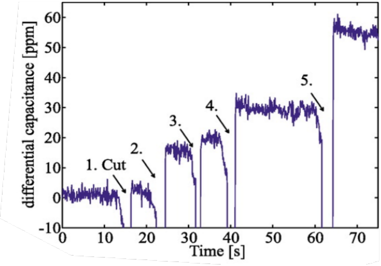
Saleem et al., "Investigation of Dynamic Properties of a Novel Capacitive-based Sensing Skin for Nondestructive Testing".

SEC's durability

The durability of the SEC has been investigated for mechanical damage.



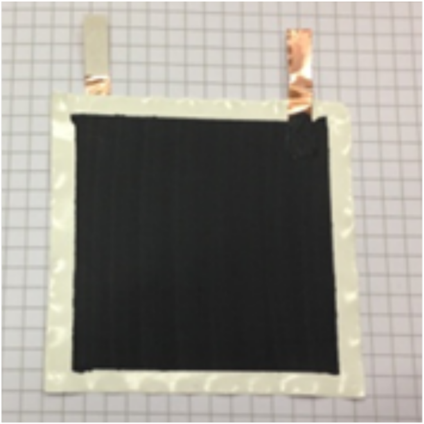




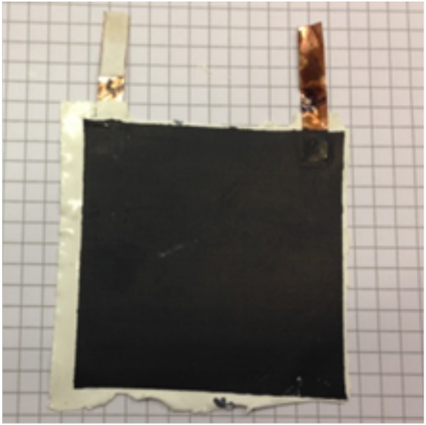
Laflamme et al., "Robust Flexible Capacitive Surface Sensor for Structural Health Monitoring Applications".

SEC's weatherability

The weatherability of the SEC has been investigated using an accelerated weathering chamber that simulated thermal, humidity, and UV radiation cycles.



0 day

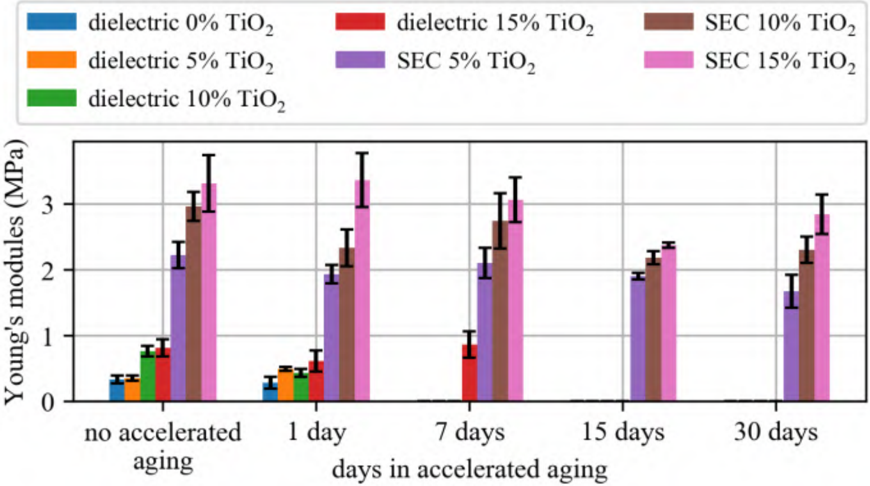


30 days

Downey et al., "Durability assessment of soft elastomeric capacitor skin for SHM of wind turbine blades".

Material properties after accelerated aging

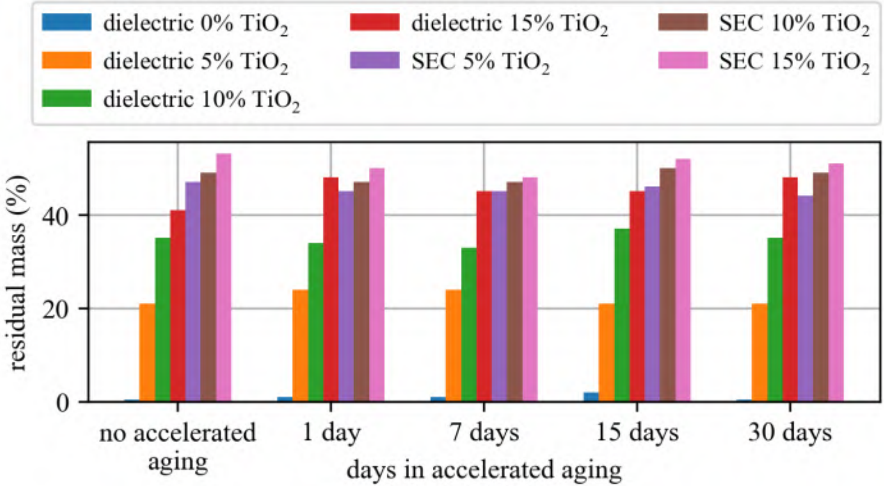
The Young's modules (E) of the samples.



Downey et al., "Durability assessment of soft elastomeric capacitor skin for SHM of wind turbine blades".

Material properties after accelerated aging

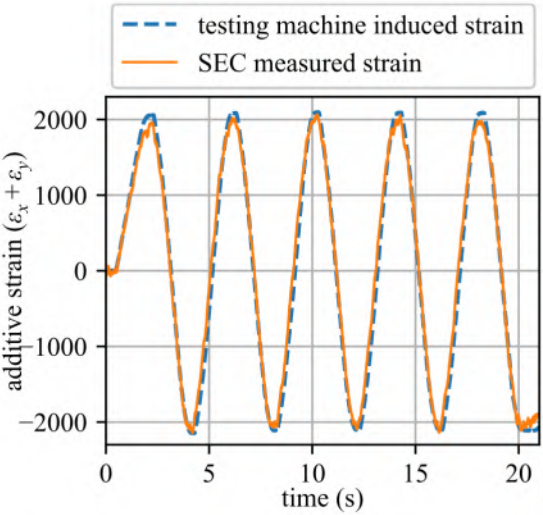
The residual mass to the samples obtained using thermogravimetric analysis.



Downey et al., "Durability assessment of soft elastomeric capacitor skin for SHM of wind turbine blades".

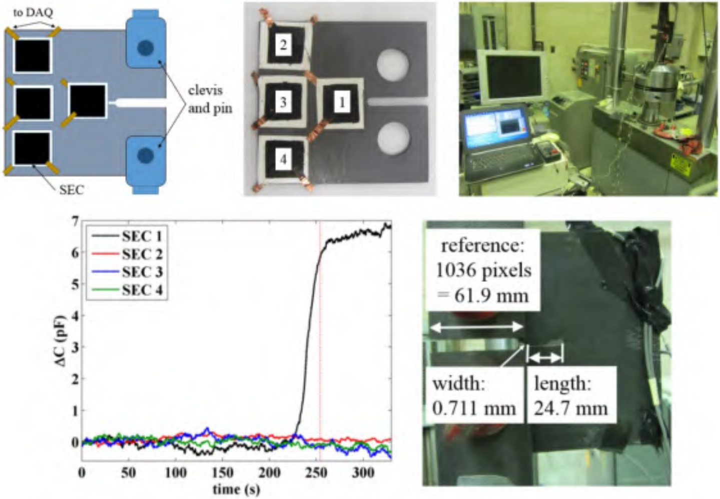
Strain testing aged SECs

Strain testing data one year after manufacturing with 30 days of accelerated aging.



DSN for fatigue crack detection

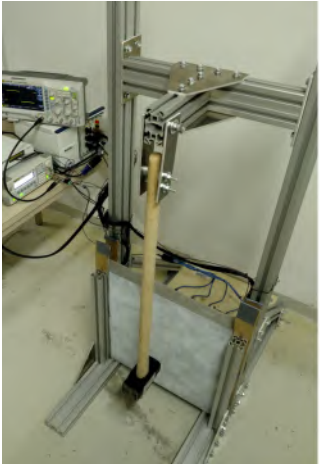
SECs deployed in a network can be used to localize damage under discrete sensors.



Kharroub et al., "Smart sensing skin for detection and localization of fatigue cracks".

Direct damage detection

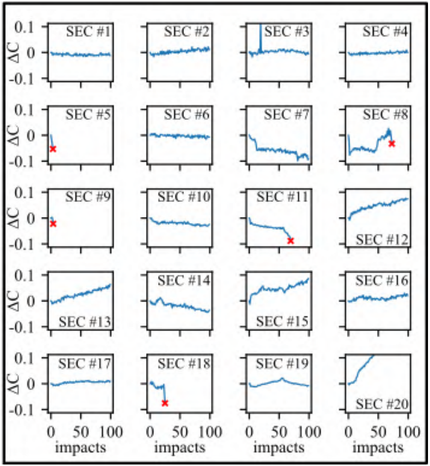
A dense sensor network of SECs is capable of spatial and temporal damage detection when deployed on a structure.



Downey et al., "Crack detection in RC structural components using a collaborative data fusion approach based on smart concrete and large-area sensors".

Direct damage detection

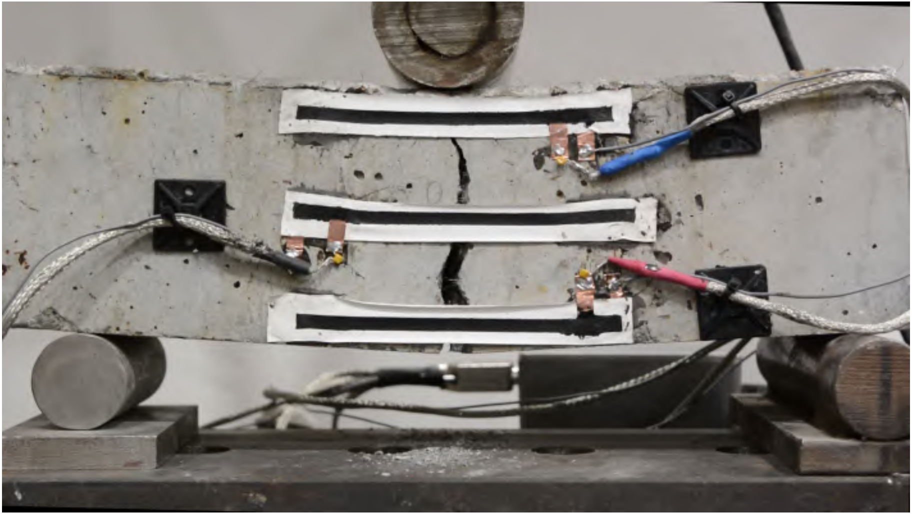
A dense sensor network of SECs is capable of spatial and temporal damage detection when deployed on a structure.



Downey et al., "Crack detection in RC structural components using a collaborative data fusion approach based on smart concrete and large-area sensors".

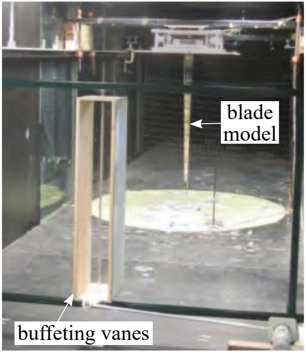
Monitoring large damage

The highly elastic SECs can be used for monitoring large cracks.

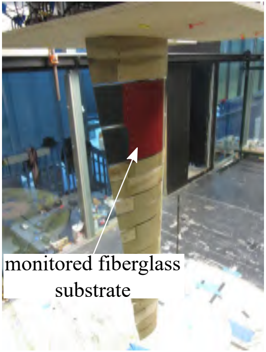


Dynamic reconstruction of unidirectional strain maps

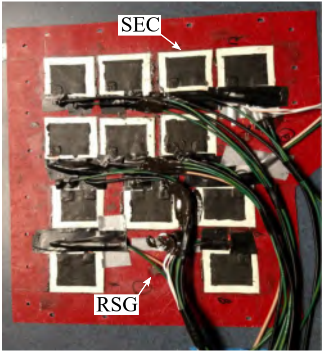
A wind turbine blade application.



buffeting vanes for generating turbulence



wind turbine blade



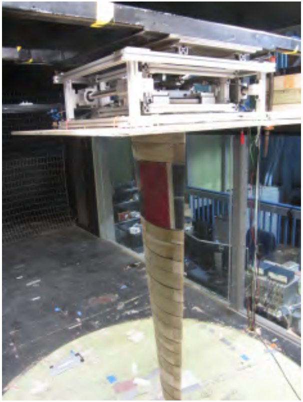
DSN installed inside model

Link

Unidirectional strain maps

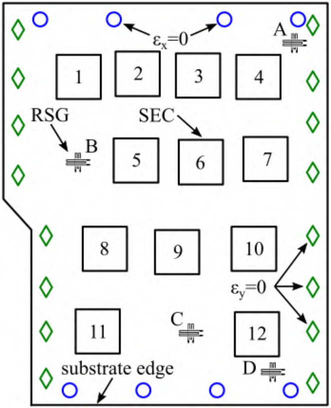
Dynamic unidirectional strain maps generated for a model wind turbine blade.

Wind Tunnel Testing



Link

Strain Maps



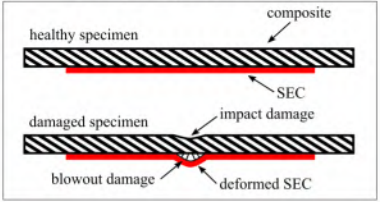
Link

Downey, Laflamme, and Ubertini, “Experimental wind tunnel study of a smart sensing skin for condition evaluation of a wind turbine blade”.

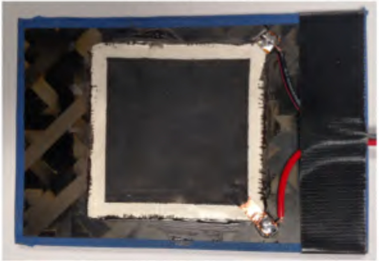
Experimental drop tower testing

Initial testing were undertaken on a custom woven composite.

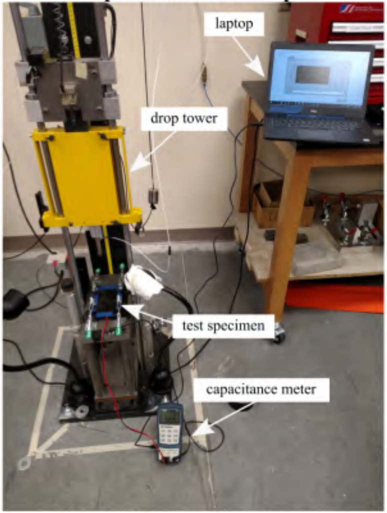
damage detection concept



tested specimen

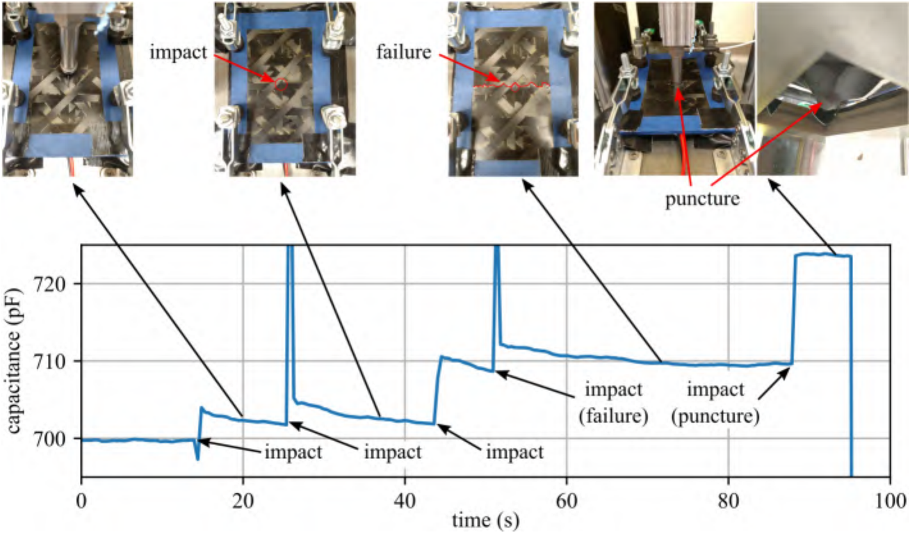


experimental test setup



Results from experimental drop tower testing)

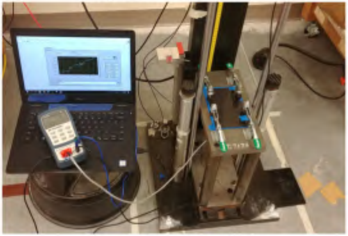
Continuous testing shows the step-wise increases



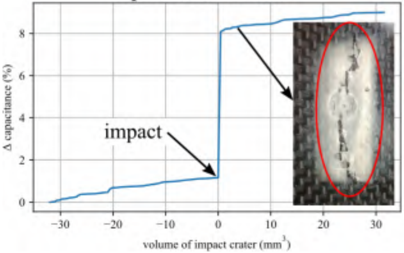
Large damage with single impact

A single drop test was performed investigated using scanning acoustic microscopy.

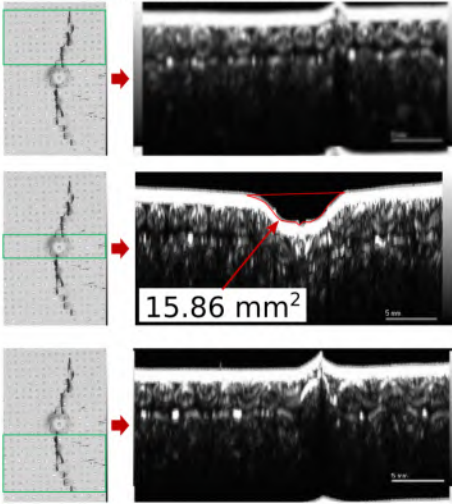
experimental setup



capacitance vs. time

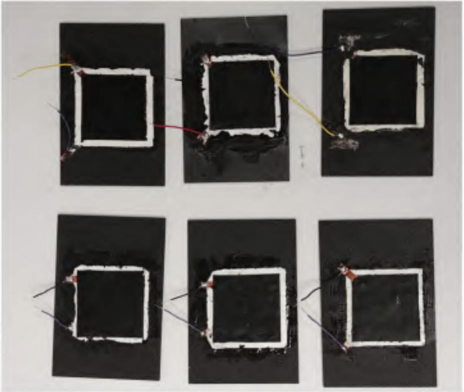


scanning acoustic microscopy

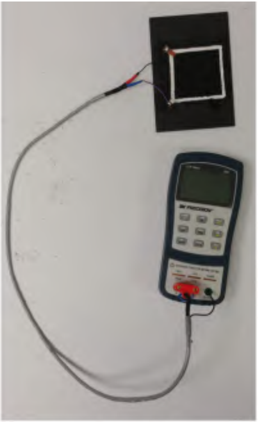


Quantify barely-visible impact damage

A larger sample set was constructed quantify sensitivity of the sensing skin.



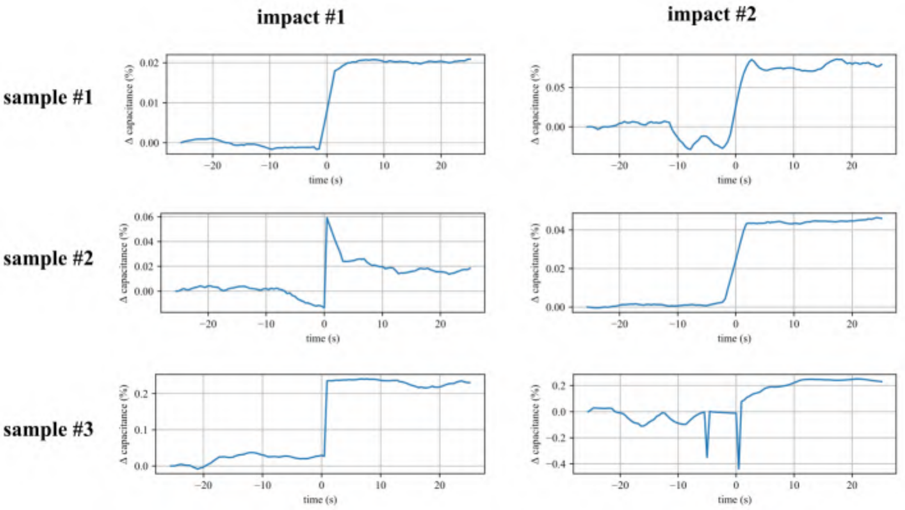
density: 0.055 lb/in^3
ply orientation: woven 0/90 and ±45
fiber modulus: 33 Msi
fiber modulus: 33 Msi



LCR: BK precision 880
sample speed: 1.5 samples/sec
accuracy: 1.25%+5 digits ≈ 0.001 pF

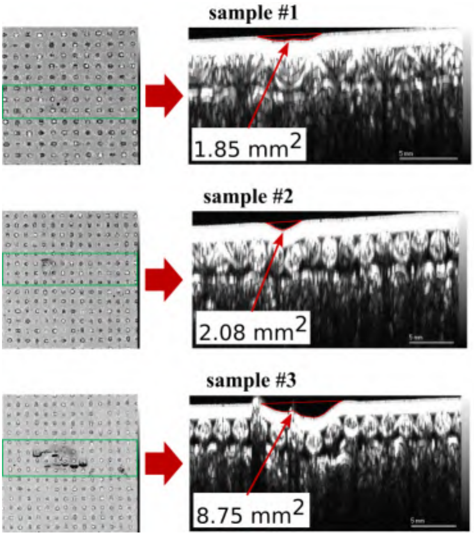
Results for 3 samples

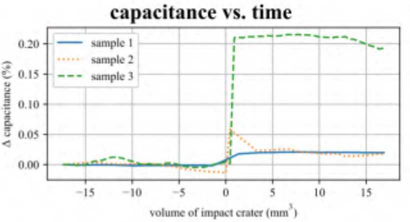
Temporal results for 3 sensors with 2 successive impacts demonstrate that noise is an issue.

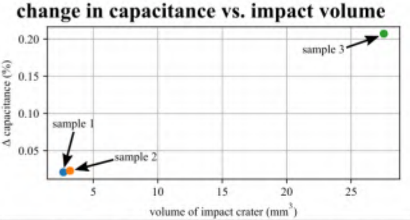


Sensitivity of the SEC sensor for impact detection

Sensitivity results for the SEC sensor are quantified on the volume of the impact crater.







Transducer frequency: 50 MHz	Scanning area: 30 mm X 45 mm around the impact
C-scan area 30 x 30mm	P-scan depth 30mm x thickness
C-scan resolution: 1000x	P-scan resolution: 500x

Summary

The research presented preliminary results into the use of a SEC-based sensing skin for impact detection in woven composites. This research:

- Demonstrated that the SEC can be used for impact detection.
- The SEC is relativity sensitive to impact damage on thin composites.
- Significant noise is present during impact testing.

Future research will:

- Quantify the minimum level of detectable damage.
- Investigate deformation under the sensors.