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Large Area Capacitive Sensors for Impact Damage Measurement

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ABSTRACT

Impacts in fiber reinforced polymer matrix composites can severely inhibit their functionality and lead to failure of the composite prematurely. This research focuses on determining the efficacy of a novel capacitive sensor, termed as the Soft Elastomeric Capacitor or SEC, for the purpose of monitoring the magnitude of out-of-plane deformations in composites. This work aims to forward the development of a sensing skin that can be used as an in situ monitoring tool for composites. The capacitive sensor can be made to arbitrary sizes and geometries. The sensor is composed of an elastomer composite that inherits the strains of the material it is bonded to. The structure of the sensor, manufactured to function as a parallel plate capacitor, responds to impacts by transducing strains into a measurable change in capacitance. In this work, the large area capacitive sensors are deployed on randomly oriented fiberglass-reinforced plate with a polyester resin matrix. The material is impacted at various energy levels until the material reached its yielding point. The behavior of the sensor in impacts below the proof resilience shows little to no change in capacitance of the sensor. As the impacts surpassed this yielding point, the sensor responds linearly with induced change in area. The results performed within expectations of the proposed model and demonstrated the efficacy of the proposed large area sensor as a damage quantification tool in the structural health monitoring of composites.

Keywords: SHM, soft elastomeric capacitor, composites, impact damage

1. INTRODUCTION

Composites can experience permanent losses in stiffness caused by impacts without incurring visible damage on the surface of the composite. Non-destructive testing methods used to detect, localize, and quantify impact damage in composites include acoustic emission, ultrasonic imaging, and radiography. The implementation of these non-destructive testing methods incurs non-trivial opportunity costs through increased down-time or the removal of certain composite parts that cannot be inspected in situ.[1]

Integrating appropriate sensing solutions with structures is a defining task of Structural Health Monitoring (SHM). The goal of these solutions is to move the modality of structural maintenance from reactive and schedule-based state assessments to data-enabled condition-based assessments. The field of SHM can be split into two branches, global and direct. Global SHM consists of measuring the structure's global dynamic response and detecting damage through changes in the measured response when compared to a healthy state. The benefits of this approach include the ability to detect damage anywhere on the structure and reduced sensor density. However, challenges can arise in the localization and quantification of damage.[2]

Direct SHM utilizes localized measurements and takes direct measures of strain at intervals along the structure. These strain transducers can only inform about the state of the material where they are attached, as such they can easily miss cracking in the material. To remedy this issue, dense sensor networks that consist of either large sensing sheets or multiple direct strains sensors have been proposed to help ensure the detection of

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localized faults (i.e. damage).[3] In this work, the Soft Elastomeric Capacitor (SEC) is studied as a tool to detect impact damage in composites. The SEC is a novel sensor that is made of an elastomeric matrix bearing the electromechanical properties of a parallel plate capacitor.[4] The sensor's response is linearly proportional to the areal deformations beneath it, similar to how a traditional resistive strain gauge is linearly proportional to the longitudinal deformations it experiences. The SEC benefits from its low manufacturing cost and high scalability, allowing a single sensor to cover large enough areas to practicably contain cracks. In a dense sensor network, the SEC is capable of damage detection, localization, and quantification on large structures.[5]

This study aims to explore the SEC's behavior in observing failure in composites due to impact and how it aligns with current electro-mechanical sensor models and sensor response expectations. This study will apply several measures to quantify the exact energy levels induced in the plate samples with a large sample set. The study material used is a standard glass fiber reinforced composite with a qualified proof resilience and the samples were prepared according to ASTM standards D7136/D7136M with a drop tower design to produce impacts within the desired range. This study shows the efficacy of the SEC sensor in out-of-plane deformation caused by impact. Experimental results indicate the measured change in capacitance aligns with the measured impact damage. The sensors showed consistently significant responses when the plates surpass their nominal resistance to impact damage proportional to the amount of damage sustained.

2. BACKGROUND

The SEC has been used in several applications prospectively with materials in the civil field. The sensor has been vetted in fatigue crack monitoring, cracking in concrete, quantifying plane strains in hybrid sensor networks, and more.[6,7] The novelty this study brings is in monitoring both the in plane and out-of-plane deformations associated with impact damage. The sensor ideally should be able to inform of potential failure in the composite. The evidence for this expectation is to be covered in this section, including the principles behind how the sensor transduces the strains to a measurable change in capacitance.

The SEC is an elastomer that can stretch up to 500% its original length in each dimension without yielding, allowing non-hysteric responses in most applications measuring strain up to 25 ε. The base elastomer is styrene-ethylene-butylene-styrene (SEBS), this material is then modified to instate its electrical properties. SEBS is chemically stable and weather resistant making them suitable for prolonged deployment in many environments.[6,7] The dielectric is formed from dispersing titania into the solution, the liquid is then dropcast and left to evaporate. The conductive plates are formed from the same liquid SEBS base with carbon black added to increase the conductivity. This conductive solution is layered onto the dielectric, allowing each layer to fully dry until a sheet resistance off 1 kΩ is reached.[4] Copper contacts are added for interfacing with data acquisition systems.

In modeling the relation of the SEC's electrical properties to its physical properties the formulation for the parallel plate capacitor is used, shown in Eq. 1. In this relationship, the capacitance C is equivalent to the ratio of the area of the conductive plates, for a square plate, $l \cdot w$ over the distance between the plates d by a factor of the permittivity of free space ϵ_0 and the relative permittivity of the dielectric ϵ_{r}.

$$C = \epsilon_0 \epsilon_{\mathrm{r}} \frac{lw}{h} \tag{1}$$

By taking the gradient of the expression of capacitance in Eq. 1 an expression for the change in capacitance can be derived as shown in Eq. 2.

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

For small uniform strains within the sensor the derivative maybe approximated by the finite difference shown in Eq. 2. Normalizing this small change by the initial a capacitance yields an Eq. 3 directly relating strains to the change in sensor capacitance.

$$\frac{\Delta C}{C_0} = \frac{\Delta w}{w} + \frac{\Delta l}{l} - \frac{\Delta h}{h} = \varepsilon_{\mathrm{w}} + \varepsilon_{\mathrm{l}} - \varepsilon_{\mathrm{h}} \tag{3}$$

By application of Hooke's stress strain relation under the plane stress assumption the substitution of the ε_{h} into Eq. 3 with the definition in Eq. 4 yields Eq. 5.

$$\varepsilon_{\mathrm{h}} = -\frac{\nu}{E}\left(\sigma_{\mathrm{l}} + \sigma_{\mathrm{w}}\right) = -\frac{\nu}{1-\nu}\left(\varepsilon_{\mathrm{l}} + \varepsilon_{\mathrm{w}}\right) \tag{4}$$

$$\frac{\Delta C}{C_0} = \frac{1}{1-\nu}\left(\varepsilon_{\mathrm{w}} + \varepsilon_{\mathrm{l}}\right) \tag{5}$$

This allows physical a interpretation of the change in capacitance of the sensor and the state of the study mateirial it is attached to.[8]

Proof resilience describes the ability of a material to accept strain energy without yielding. Yielding past this point stores the energy used to do so as a nonconservative loss. Due to the impacts intentionally transgressing the plastic region of the plate, the mechanical energy losses can be tracked to allow observation of the strain energy retained in the plate. By tracking the impact velocity of the impactor and the force measured by the impactor's load cell the energy absorbed into the plate can be derived, as detailed more thoroughly in ASTM D7136/D7136M.

$$E_{\mathrm{sys}}(t) = T_{\mathrm{kinetic}}(t) + U_{\mathrm{graviational}}(t) - U_{\mathrm{strain}}(t) = 0 \tag{6}$$

While observing the impact event from the time of contact until the impactor leaves the sample the simplification in Eq. 6 holds, while ignoring small losses to heat and sound, as the friction with the rails is minimal.

$$\Delta U_{\mathrm{strain}} = \Delta T_{\mathrm{kinetic}} + \Delta U_{\mathrm{graviational}} \tag{7}$$

The total energy stored in the plate ($\Delta U_{\mathrm{strain}}$) can be stated to be equivalent to be the total change in the mechanical energies of the impactor shown in Eq. 7 while in contact with the composite plate. The integration of the load cell signal yeilds the change in momentum of the impactor. By then scaling the momentum by the mass of the impactor velocities can be retreived as shown in Eq. 8.

$$\Delta U_{\mathrm{strain}} = \frac{m(V_{\mathrm{f}}^2 - V_{\mathrm{i}}^2)}{2} + mg\Delta h \tag{8}$$

where V_{f} and V_{i} are the velocity of the impactor leaving and entering respectively the impact event while m, g, and Δh are the mass of the impactor, the acceleration due to gravity, and change in height of the impactor head, respectively.

3. METHODOLOGY

The sample-set uses ASTM D7136/D7136M for measuring the damage resistance of a composite in a drop-weight impact event. The exact specification of the drop tower used follows in the equipment section according to the reported procedure in ASTM D7136/D7136M. The use of these procedures allows the work done by the composite plate to be retrieved for each trial and compared to the measured capacitance change. The expectation is to observe a large change in capacitance of the SEC in impacts where the proof resilience is exceeded representing the sensor has observed failure of the material.

The capacitance measure is taken by a B&K Precision model 891 at a test frequency of 1 kHz and a sampling frequency of 45 S/s. For the measure of capacitance in the trial, given the dynamic nature of the testing, the cabling used is of great concern. Tri-axial cabling is used to isolate the measure as thoroughly as possible from mechanical perturbation of the cabling from affecting the signal. The ground plane of the SEC, as in prior applications, is attached to the sample to aid in signal isolation. All objects that are in contact with the sample are included in the ground plane by extension of this principle including the impactor mass, drop tower, peripheral equipment, and any contact by researchers. The drop tower is constructed to the ASTM standard with an allowable exception for the impactor mass which is reported as non-standard at 7.5 kg mass. The Impactor

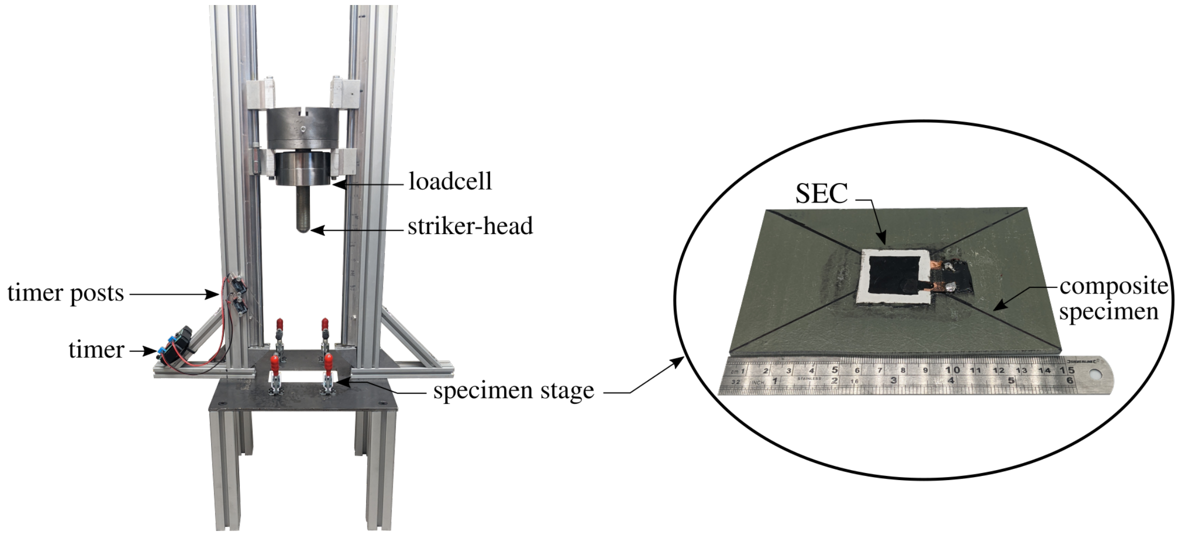

Figure 1. Depicted on the left is the drop tower and on the right is the bottom side an example specimen of composite GFRP plate, 4 by 6 in, with an SEC mounted opposite the impact site, 1 by 1 in.

head comports with the hemisphere requirement and the support fixture follows all dimensioning outlines. The timing unit is positioned with its last post 0.5 cm before impact read at microsecond intervals. The loadcell is a pancake type Honeywell model 43 sampled at 15,000 S/s in compliance with standards.

4. RESULTS

The sample set contains 25 individual samples impacted with varying levels of energy. The measures taken for each sample include measuring the capacitance, force, and impact velocity. These measures are used to derive the work done on the plate during the impact. The impact energy is stochastically related to failure in the plate due to individual differences in the plate material and manufacturing quality. The composite's failure modes in random orient fiber are not practicably predictable. The SEC is captured and transduces the aggregate deformation over the area of application. The sensors chosen are large enough to contain the entire damaged region, deduced from a pre-trial run of impacts.

The trial showed the expected response after the nominal proof resilience of the composite. The proof resilience of the composite, its maximum nominal resistance to impact damages of a certain energy level, from 2.88 J to 5.08 J. The observed change in the measured normalized capacitance occurs above the nominal proof resilience where the composite exhibits failure. In Fig. 2a) a clear trend is shown with an increase past the expected point of failure. The procedure to retrieve the work done by the plate deformation is outlined in Eq. 8. The impact velocity and the force curve under the are used to determine the work done on the impactor head by the plate. In Fig. 2b) the work done by the plate on the impactor head is shown where an increase in the measured capacitance can be seen as the energy absorbed by the plate increases.

5. CONCLUDING REMARKS

The trial demonstrated the efficacy of the SEC in determining the failure in the composite plates. 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. The sensors were observed to respond predictably to the expected material behavior. The sensors were observed to respond as expected responding when the materials rated impact limit had been surpassed. Future work looks to validate these results with measures of surface deformation explicitly with the normal changes in capacitance.

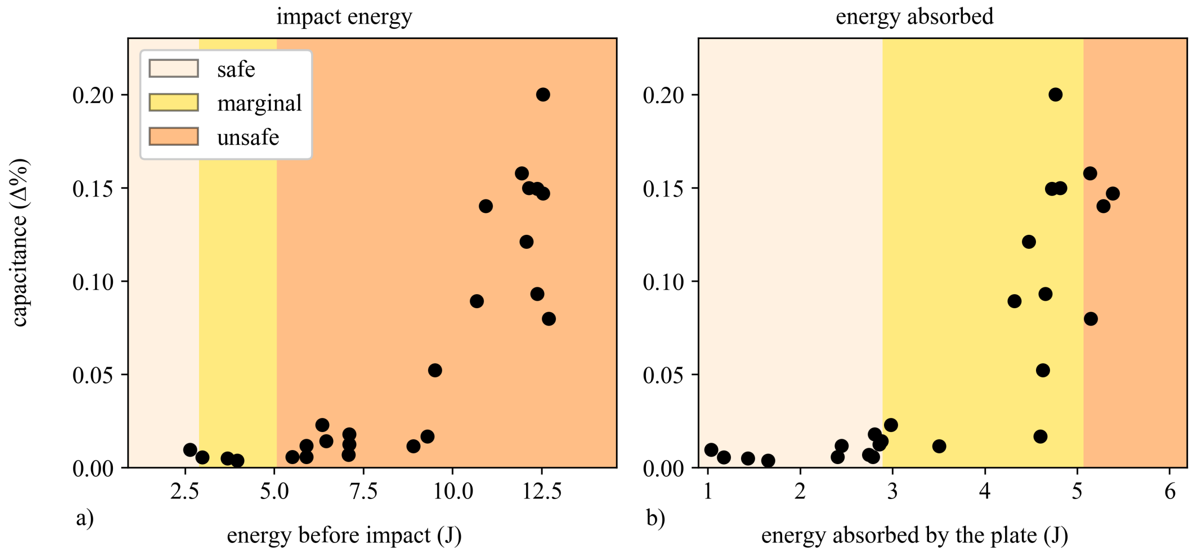

Figure 2. the total 25 sample data set visualized with respect to the materials impact resistance: a) details the capacitive response with respect to the energy before impact and; b) details the capacitive response with respect the energy absorbed by the plate.

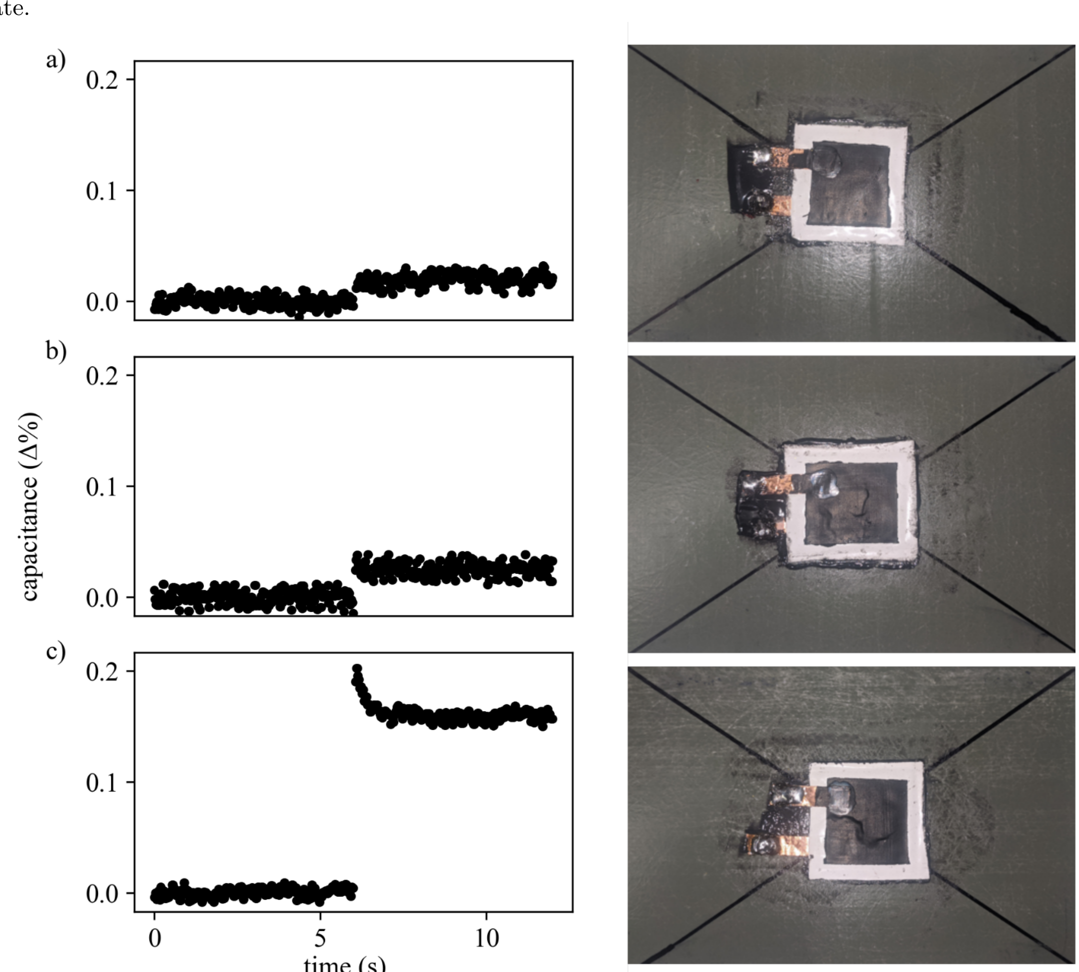

Figure 3. Selected samples from the safe, marginal, and unsafe regions with of Fig. 2b): a) depicts a sample in the safe region subjected to a 1.03 J impact; b) a sample in marginal region subjected to a 2.84 J impact, and; c) a sample in unsafe region subjected to a 5.14 J impact.

6. ACKNOWLEDGMENTS

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REFERENCES

[1] Gunes, B. and Gunes, O., "Structural health monitoring and damage assessment part i: A critical review of approaches and methods," *International Journal of Physical Sciences* **8**(34), 1694–1702 (2013).

[2] Mei, H., Haider, M. F., Joseph, R., Migot, A., and Giurgiutiu, V., "Recent advances in piezoelectric wafer active sensors for structural health monitoring applications," *Sensors* **19**(2), 383 (2019).

[3] Hu, Y., Rieutort-Louis, W. S., Sanz-Robinson, J., Huang, L., Glišic, B., Sturm, J. C., Wagner, S., and Verma, N., "Large-scale sensing system combining large-area electronics and cmos ics for structural-health monitoring," *IEEE Journal of Solid-State Circuits* **49**(2), 513–523 (2014).

[4] Laflamme, S., Ubertini, F., Saleem, H., D'Alessandro, A., Downey, A., Ceylan, H., and Materazzi, A. L., "Dynamic characterization of a soft elastomeric capacitor for structural health monitoring," *Journal of Structural Engineering* **141**(8), 04014186 (2015).

[5] Yan, J., Downey, A., Cancelli, A., Laflamme, S., Chen, A., Li, J., and Ubertini, F., "Concrete crack detection and monitoring using a capacitive dense sensor array," *Sensors* **19**(8), 1843 (2019).

[6] Kong, X., Li, J., Bennett, C., Collins, W., and Laflamme, S., "Numerical simulation and experimental validation of a large-area capacitive strain sensor for fatigue crack monitoring," *Measurement Science and Technology* **27**(12), 124009 (2016).

[7] Downey, A., Yan, J., Laflamme, S., and Chen, A., "Dynamic reconstruction of in-plane strain maps using a two-dimensional sensing skin," *Structural Health Monitoring 2017* (shm) (2017).

[8] Liu, H., Laflamme, S., Li, J., Bennett, C., Collins, W. N., Downey, A., Ziehl, P., and Jo, H., "Soft elastomeric capacitor for angular rotation sensing in steel components," *Sensors* **21**(21), 7017 (2021).