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Impact sensing and localization in composites structures with embedded mechanoluminescence-perovskite sensors

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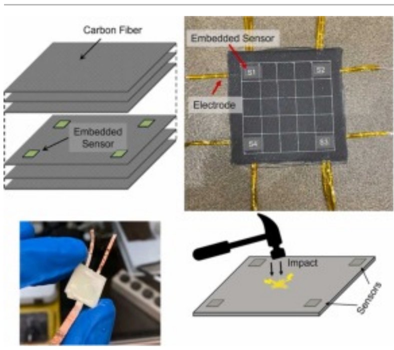
Abstract

Mechanoluminescence (ML)-perovskite sensors have shown potential for real-time impact sensing in composites structure. The sensors can be embedded in the structure for in-situ and real-time structural health monitoring (SHM) applications. Our previous work demonstrated the potential of a flexible ML-perovskite sensor for SHM systems and the possibility of sensor embedment in a fiber-reinforced composite structure. However, the viability of the sensor to predict impact localization remains unexplored. This paper investigates the potential of the sensors for impact localization in composite laminates. Herein, embedded ML-perovskite sensors are placed throughout a composite plate to monitor the host structure. By monitoring and correlating the changes in the electrical current of the sensors, it is possible to predict the impact location in the structure. The experimental results show that the ML-perovskite sensor can accurately detect and locate impact events when embedded in a composite structure. This work reveals the potential of ML-perovskite sensors for damage detection and localization prediction in composite materials.

Graphical Abstract



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Introduction

The demand for advanced composite materials has increased exponentially over the past years due to their attractive properties, such as the tremendous performance-to-weight ratio. This increasing demand for composite structures has created a need to monitor their integrity and performance during service [1], [2], [3]. The detection, monitoring, and evaluation of composite structures are complex due to their anisotropic nature. Moreover, detecting damage caused by impact events in composite structures is challenging. Minor impact events, such as tool drops and low energy impacts, can cause barely visible damage (BVID) in composite structures. BVID is responsible for causing damage inside the composite structure, and no suggestive evidence on the structure's surface. Because of that, BVID is not easily detected by established non-destructive techniques (NDT) [1], [2], [3], [4], [5], [6], [7], [8]. However, the internal damages can compromise the structural integrity within the composite, causing delamination, matrix cracking, fiber fracture, and fiber pullout. Therefore, it is vital to detect these minor impact events that happen to a composite structure during service.

Traditionally, the assessment of impact damage is conducted by NDT like ultrasonic inspection, acoustic emissions, or visual inspections [9], [10], [11], [12], [13]. However, since they are primarily external techniques, all the instrumentation and sensors necessary for the testing must be assembled on the surface or close enough to the tested part. The structure often must be put out of service to conduct these methods, which can be very difficult and challenging. There is a need to develop novel sensors with improved architecture, sensitivity, and performance for structural health monitoring (SHM) applications. SHM enables intrinsic monitoring of the structural conditions of a part [1], [2], [14], [15], [16].

SHM systems for damage localization in composites have been developed employing embedded sensors such as optical fiber sensors, piezoelectric sensors, and carbon nanotube sheets [17], [18], [19], [20], [21]. Dziendzikowski et al. [22], [23] conducted comparison research on BVID detection and localization in composites using surface-mounted and implanted PZT transducers. Because of their higher interaction with the structure, the embedded sensors have better BVID detection capabilities than surface-attached sensors of the same type [22].

Impact localization in composites was achieved by Aly and Bradford et al. [24] using embedded aligned carbon nanotube (CNT) sheets. This is done by concurrently detecting the in-plane electrical resistance changes of the CNT sheets and correlating them to the impact damage modes in the structure. Kwon et al. [25] described a piezoresistive sensor based on SiC fibers. The SiC fiber sensor network was embedded in a composite panel. Impact signals were recorded utilizing the resistance variations of the embedded SiC fibers, and the impact localization was calculated using the centroid technique.

Mechanoluminescence (ML)-based sensors are also proposed to monitor and detect damage in composite structures [26], [27], [28], [29]. The light emission caused by mechanical stimuli on the material is referred to as ML. ML light emission is sensitive to stress and can be utilized to assess the damage in composites. Applications for ML-based devices include ML stress sensors [30], [31], pressure mapping [32], dynamic load sensing [33], and structural health monitoring [33], [34], [35]. Okoli et al. [35] created an in-situ triboluminescent optical fiber (ITOF) sensor based on ML that may be integrated into a composite for damage localization. Non-contact detection is a significant benefit of ML-based sensors. However, most ML devices and sensors require costly and complex photo-collection equipment to gather and analyze light emissions, such as photomultiplier tubes, spectrometers, or CCD cameras. They are not fully integrated, which may result in decreased performance and practical applications [34], [36]. The ML-perovskite sensor combines an ML-based sensor with a high-performance photodetector device, which prevents light loss from the ML layer and makes the sensor more efficient than traditional ML-based sensors [34]. Most ML sensors need to be attached to the structure's surface for the light information to be collected by external equipment. Because the light is collected in situ, the ML-perovskite sensor can also be embedded in dark structures, such as carbon fiber composites.

This work assessed the capabilities of embedded mechanoluminescence (ML)-perovskite sensors for impact localization in composite structures subjected to low energy impacts. The ML-perovskite sensor acts as a passive sensor, collecting signal information after an impact event [34], [37]. The sensor was fabricated using a flexible and simple design, consisting of a planar architecture of zinc sulfide:copper (ZnS:Cu)/polydimethylsiloxane(PDMS)/indium doped tin oxide (ITO)-Polyethylene terephthalate (PET)/tin (IV) oxide (SnO_2)/perovskite/Carbon, as seen in Fig. 1(a). The ML-perovskite sensor is self-powered, flexible, and robust. It can be fabricated using a straightforward device architecture, a tremendous advantage of ML-based sensors over more traditional technologies, such as piezoelectric devices [33], [36], [37].

The composite panel with an embedded ML-perovskite sensor network was fabricated by embedding the sensors in a composite structure. The structure was subjected to different impact impacts, and the location of the impact events was estimated using the concept of the centroid of points [38], [39], [40]. The sensors showed performance comparable to other reported sensors used for damage localization, as shown in Table 1. The sensors could detect energy impacts as low as 0.6 J, showing good potential for low-energy impact detection.

Section snippets

Sensor fabrication

A sequential fabrication process was employed in the fabrication of the ML-Perovskite sensor. All materials were purchased from Sigma-Aldrich unless stated otherwise. Essentially, PET/ITO substrates were cut and patterned by etching with hydrochloric acid (HCl) and zinc (Zn) powder. After cleaning, the PET substrates were treated with oxygen plasma for 5 min before depositing an ETL and perovskite. The SnO_2 precursor (Alfa Aesar) was diluted with deionized water to a 1:6 vol ratio, spin-coated…

Impact sensing assessment

Impact events can be classified based on the energy level of the event. A low-energy event can damage the structure without catastrophic failure or visible damage. Impact damage can occur within the structure during the low energy impacts, causing matrix microcracks or even delamination at the interfaces. Visual inspections or some traditional NDT techniques do not easily detect this damage. In this work, the impact velocity studied is less than 10 m/s, and the highest impact energy for impact…

Conclusions

The present study investigated a straightforward technique to detect impact events and estimate the location of different impact occurrences in a carbon fiber/vinyl-ester composite structure. In this technique, four ML-perovskite sensors were embedded in the corners of the composite structure. The centroid method was used to estimate the location of the low energy impacts with reasonable accuracy. The results showed that the sensors could potentially detect damages throughout the composite…

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CRediT authorship contribution statement

Lucas Braga Carani: Conceptualization, Methodology, Investigation, Writing – original draft. **Terrencia Martin**: Methodology, Investigation. **Vincent Eze**: Conceptualization, Visualization, Supervision, Writing – review & editing. **Okenwa Okoli**: Supervision, Writing – review & editing, Project administration.…

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.…

Lucas Braga Carani is currently an Ph.D. candidate at the Industrial and Manufacturing Engineering Department at the FAMU-FSU College of Engineering, Florida, United States. His research interest is in the development of sensors for structural health monitoring of composite structures.…

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