Mechanochromic hybrid composites for structural health monitoring

Fotouhi, Mohammad; Tabatabaeian, Ali; Harrison, Philip; Schlangen, Erik

Publication date
2024

Document Version
Final published version

Published in
Proceedings of the 21st European Conference on Composite Materials

Citation (APA)
Fotouhi, M., Tabatabaeian, A., Harrison, P., & Schlangen, E. (2024). Mechanochromic hybrid composites for structural health monitoring. In C. Binetury, & F. Jacquemin (Eds.), *Proceedings of the 21st European Conference on Composite Materials: Volume 3 - Material and Structural Behavior – Simulation & Testing* (Vol. 3, pp. 855-862). The European Society for Composite Materials (ESCM) and the Ecole Centrale de Nantes..

CONTENTS

Mechanochromic hybrid composites for structural health monitoring

Mohammad Fotouhi[1], Ali Tabatabaeian[2], Philip Harrison[2] and Erik Schlangen[1]
[1]*Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands*
[2] *School of Engineering, University of Glasgow, Glasgow, UK*

Corresponding author:
m.fotouhi-1@tudelft.nl Web Page: https://www.tudelft.nl/en/chairs0/material-health-monitoring

Keywords: Structural health monitoring, Mechanochromic, Hybrid Composites

Abstract

The present paper reports an overview of mechanochromic self-reporting thin-ply hybrid composite sensors, which are designed to visually indicate overload in structures. These sensors, made from combinations of high-strain and low-strain materials, change appearance earlier than the final fracture, providing a clear visual cue of damage like delamination or strain overload. They can be used for various applications, for example, overload monitoring, and to detect barely visible impact damage in composites.

1. Introduction

The development of mechanochromic composites for structural health monitoring (SHM) presents a novel and efficient approach to improving the safety and performance of various structures in industries like aerospace, civil, and automotive. These are based on self-reporting polymer composites which provide a light-weight sensor with an easy-to-read visual cue. These composites can sense their state of health, such as damage or deformation, through changes in colour or appearance, and do not require external data acquisition systems. They offer a user-friendly, cost-effective, and environmentally sustainable solution for SHM, with the potential for significant technological and economic benefits [1].

As summarised in figure 1, the mechanochromic composites are categorized into two primary groups: chemical-based and physical-based colors. Chemical-based colors involve the use of pigments or dyes that change color upon mechanical excitation, often through the rupture of micro-capsules or fibers containing dyes. These can be used in various composites and coatings for metals and concrete, providing a visible response to mechanical stimuli [2]. Physical-based colors, on the other hand, arise from the interaction of light with the material's structure, as seen in phenomena like the iridescent colors of butterfly wings or peacock feathers. These structural color materials can change color under different stimuli like electricity, heat, light, and strain, offering an eco-friendly alternative to traditional pigments and dyes [3].

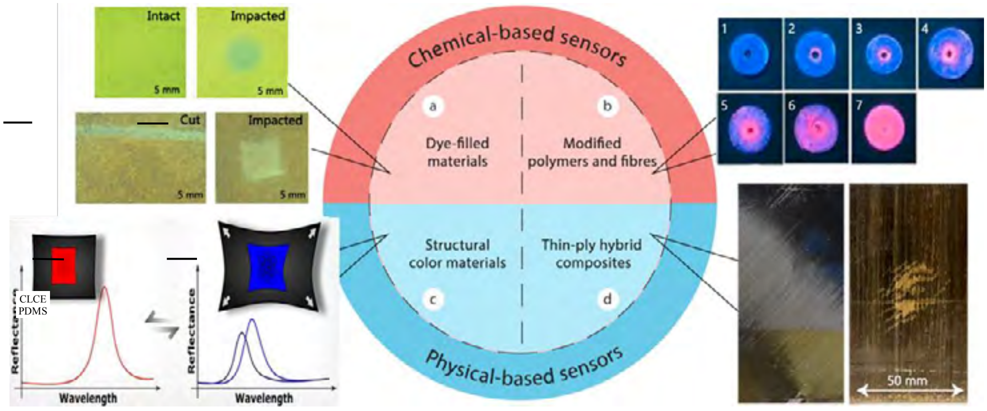

Figure 1. Examples of different mechanochromic approaches for SHM applications: a) characterisation of impact damage and cuts in polymer composites prepared with microcapsules [4], b) color changing process in composites under compression, increasing from left to right, indicating the fluorescent activation [5], c) a structural color patterns that are either always visible or reversibly revealed or concealed upon

mechanical deformation [6], d) comparison of the visual damage detection in a structure with (right) and without (left) hybrid composite sensors under the same impact loading condition [7].

The present paper reports a critical overview of mechanochromic self-reporting thin-ply hybrid composite sensors, which are designed to communicate visual information for SHM purposes. These sensors, made from combinations of high-strain and low-strain materials, change appearance earlier than the final fracture, providing a clear visual cue of damage like delamination or strain overload. They can be used for various applications, for example, overload monitoring [3], and to detect barely visible impact damage in composites [8].

2. Mechanochromism based on Glass/Carbon Hybridisation

Thin-ply hybrid composite sensors have been developed as an easily-implementable approach for visual indication of overload. These sensors are made using commercial prepregs and the sensing mechanism is activated via fracture. Different types of failure in a three-layer uni-directional hybrid laminate made from high-strain-material and low-strain-material are shown in figure 2. Damage and failure mechanisms lead to a visual indication of strain overload, where delamination is suppressed and several low strain fractures occur, followed by stable localised pull-out. This is achieved by choosing appropriate material properties, relative low-strain-material to high-strain-material thicknesses and absolute thickness of the low-strain-material [9].

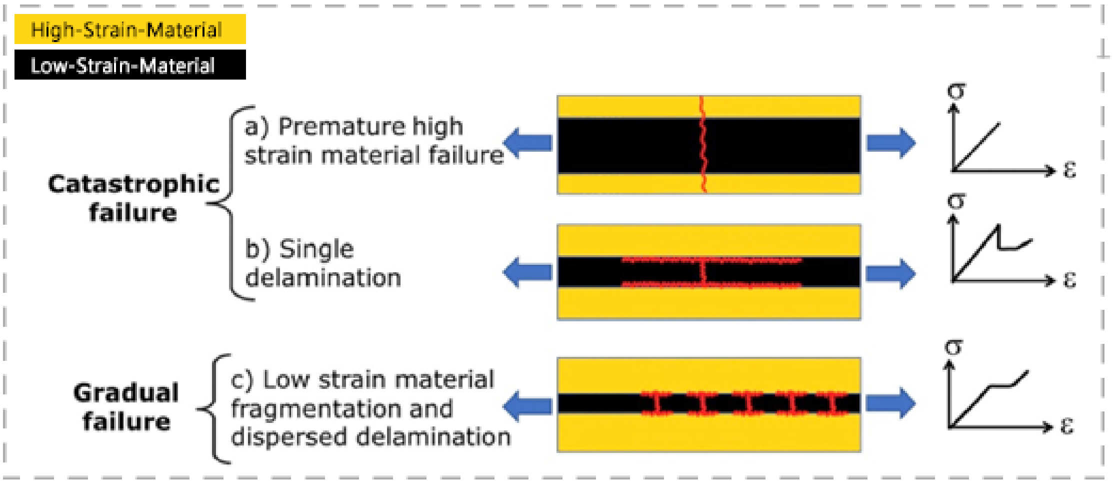

Figure 2. Different failure mechanisms in a three layer uni-directional hybrid composed of high-strain-material and low-strain-material (red lines indicate fracture) (a) single crack through the whole specimen, (b) single crack in the low-strain-material followed by instantaneous delamination, and (c) multiple fracture and localised stable pull-out of the low-strain-material [10]

Figure 3 shows two different designs of the uni-directional hybrid composite sensors, where the visual change is achieved by a purpose-designed, thin interlayer of glass/carbon-epoxy hybrid composite loaded by a predefined strain value. Light passes through the translucent glass layer and is absorbed by the intact carbon layer, creating a dark appearance. Figure 3(a) shows fragmentation of the low strain material followed by gradual, dispersed delamination [11]. The incident light is reflected from the locally damaged glass/carbon interface around the carbon layer fractures, creating light stripes. Figure 3(b) shows another type of failure in thicker carbon layers: a single fracture of the low-strain-material is followed by sudden delamination [12]. Both can act as good overload indicators since it is easy to visually monitor the delamination through the translucent glass layer.

Hybrid sensors can also be used for fatigue life monitoring, where an increase in the delamination area can be correlated to the number of cycles, as shown in Figure 4 [13].

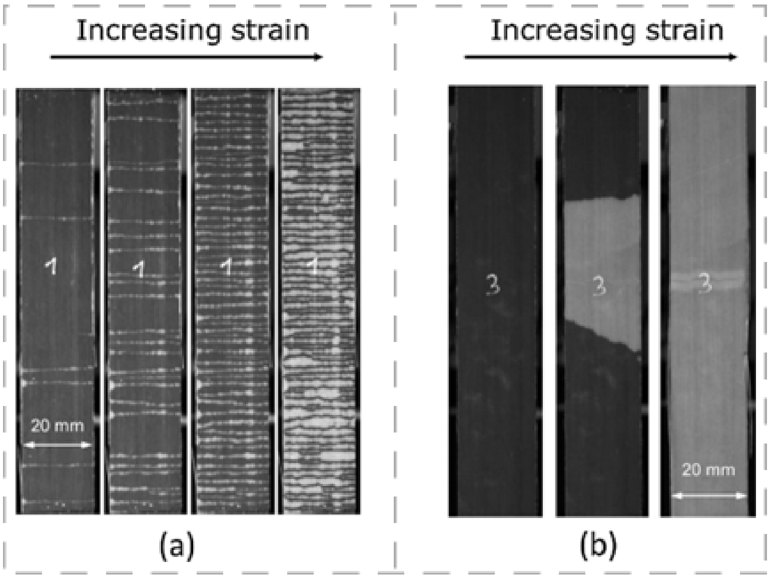

Figure 3. Visual indication of damage in thin-ply glass/carbon hybrids: (a) carbon layer fragmentation followed by stable, dispersed delamination [11], (b) carbon layer fracture followed by sudden delamination [12].

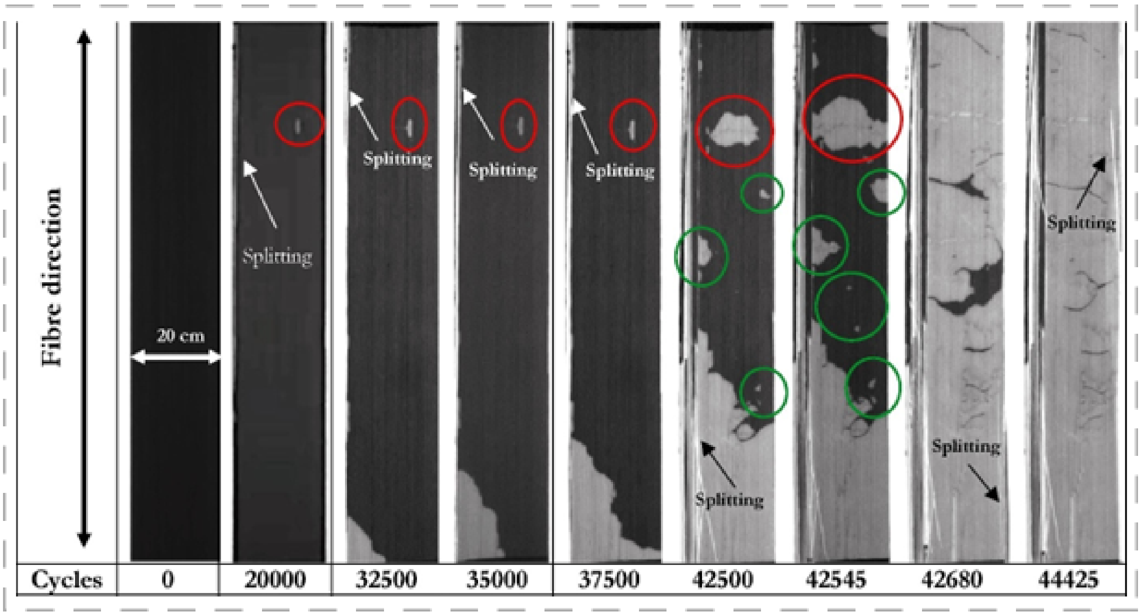

Figure 4. Fatigue life monitoring in a uni-directional thin-ply glass/carbon hybrid composite at 90% stress level of the carbon fragmentation initiation [13].

Multidirectional pseudo-ductile thin-ply hybrid laminates with improved ductility and notch insensitivity have also been developed [10,14]. These multidirectional laminates showed similar damage mechanisms to the uni-directional laminates but have the advantage of being able to monitor damage evolution, as the damage can be observed around the notches before any catastrophic failure occurs, as shown in Figure 5. Typically, hybrid composite sensors are either bonded directly onto the structures' surface or they are incorporated into the structure as a sensing layer (see Figure 6). By combining different sensing materials activated by different strains, they can provide a more detailed picture of the overload. Also, by designing an array of sensors orientated in different directions, the overload direction can be monitored. A sensor mounted on a component is subjected to the same strains as the material below. Carbon and glass layers serve as the 'sensing' and 'outermost' layers in this case.

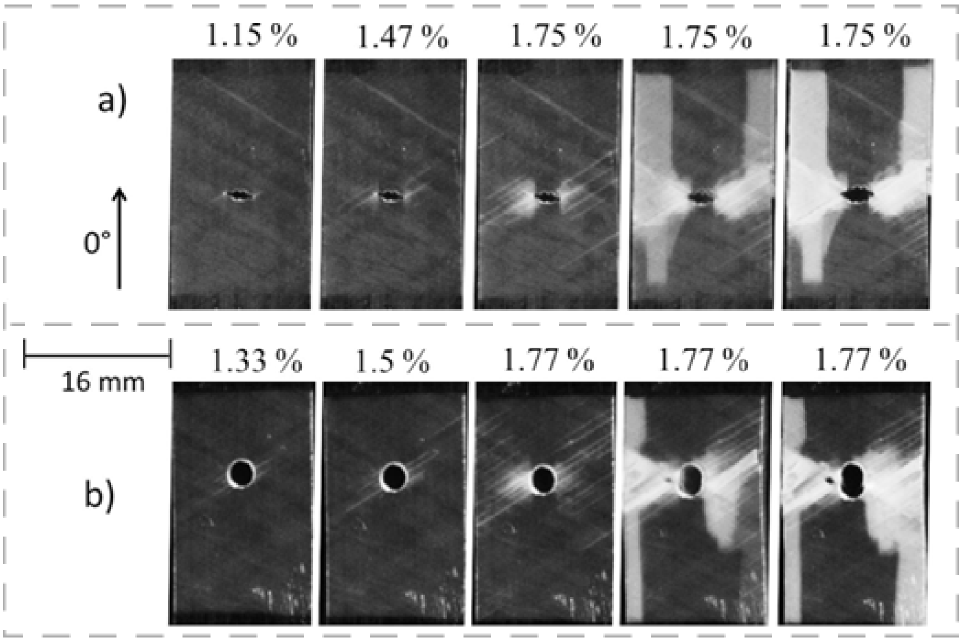

Figure 5. Visual indication of damage in (a) sharp notched and (b) open-hole ±60QI/Hexcel laminates, at different strains in tensile test [14].

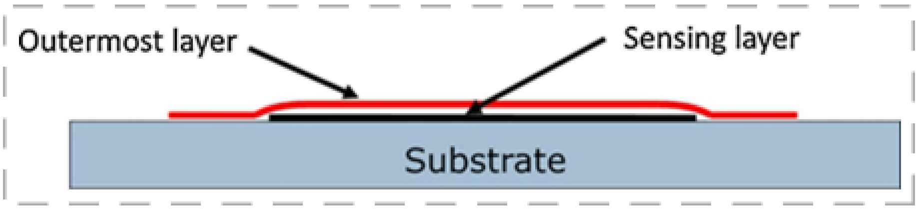

Figure 6. Schematic of a hybrid composite strain overload sensor attached to a substrate material [3].

Unlike other mechanochromic systems reviewed in previous sections the simplicity and practicality of glass/carbon hybrid sensors has led to their relatively rapid use in SHM. For example, a set of short and long sensors made of single ply XN80/EPOXY were applied on some commercially available CFRP bike handlebars, and both handlebar structures with and without sensors were tested under a three-point bending load. Figure 7 shows the force-displacement response of the tested structures, here the activation point for long sensors is between 1500 N and 2000 N. The graph also shows the load (1000 N) prescribed for testing Racing Bicycle handlebars according to the European Standard (EN14781) [15]. Results of this test suggested that sensors did not induce any noticeable increase in stiffness.

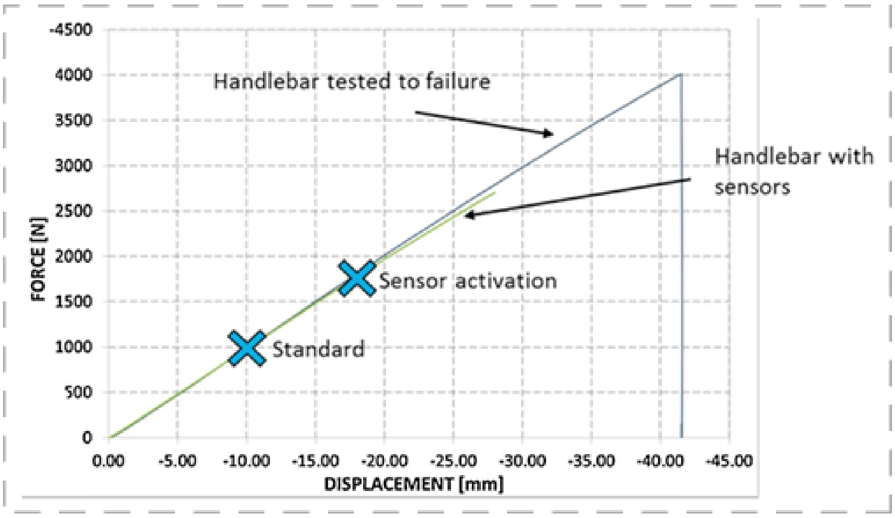

Figure 7. Force-displacement response of the tested CFRP bike handlebars [3].

Figure 8 illustrates a handlebar equipped with both short and long sensors. Here the first fracture of the long sensor was observed at 1750 N. The self-reporting concept could be successfully achieved by using long sensors, providing a warning to the user that a critical loading condition had occurred.

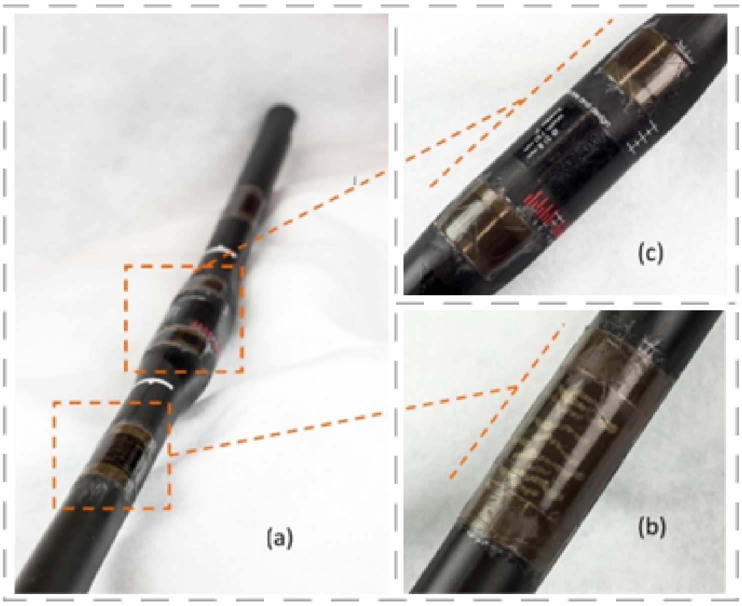

Figure 8. Bike handlebar eqipped with hybrid composite sensors: (a) MTB Racing flat handlebar, fitted with (b) long (c) short sensors [3].

A bonded composite patch is one method used to repair cracks in aluminium panels used in aerospace structures. However, in the case of standard repair techniques, damage beneath the repair patch cannot be detected by simple visual inspection alone. Therefore, hybrid composite sensors can be used as a composite repair patch which can self-report critical situations, e.g. an overload or crack extension in the substrate. As discussed earlier, these sensors are designed such that they do not change the local strain distribution. Nevertheless, in case of a repair patch, it is necessary to have enough stiffness so that the load in the substrate damaged area is reduced and carried instead by the patch. The practicality of the concept was investigated by applying a hybrid composite sensor on an aluminium panel with a 20mm initial crack length (see Figure 9).

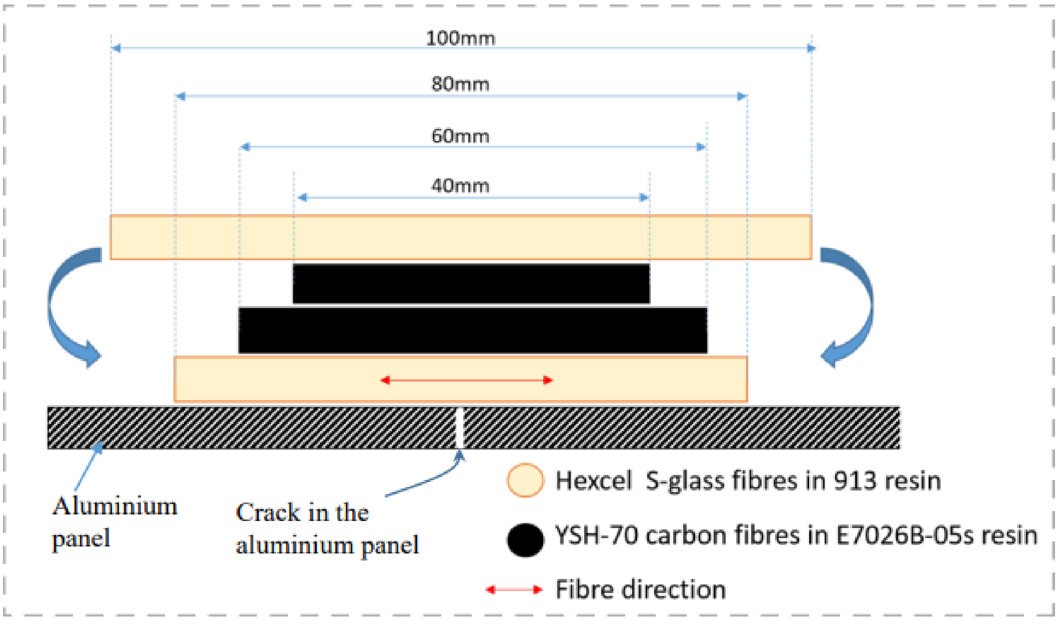

Figure 9. Schematic of hybrid composite repair patch [16].

During the quasi-static tensile test, changes in appearance were evident above the threshold load in the repaired specimen (see Figure 10). By overloading the specimen, crack propagation began beneath the repair patch. Figure 10 shows a change of appearance due to delamination, induced by fractured carbon at the centre of the specimen (above the crack), demonstrating the self-warning ability of the repair patch.

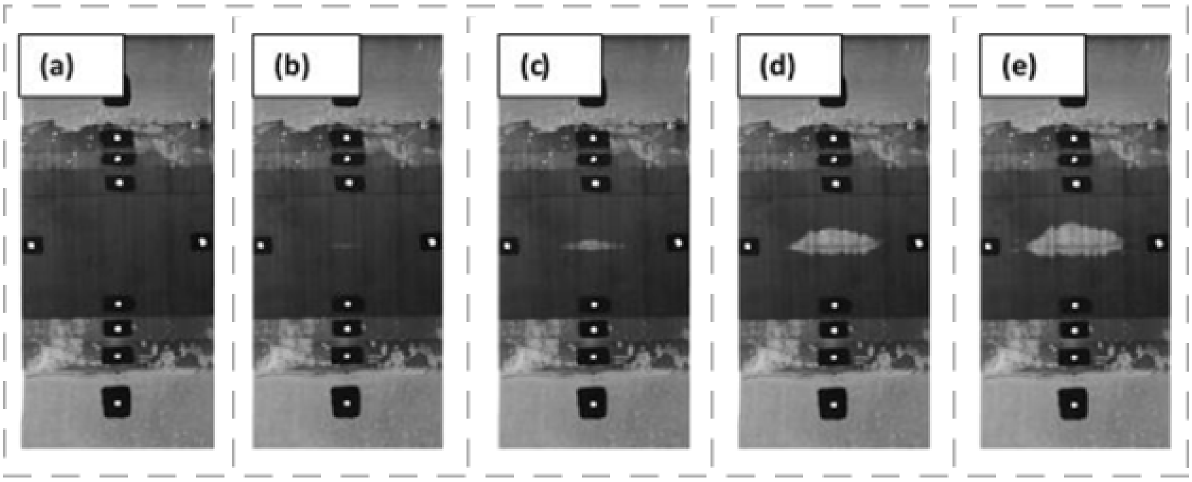

Figure 10. Self-reporting hybrid composite sensors subjected to increasing loads: (a) 195 MPa; (b) 197 MPa; (c) 304 MPa; (d) 336 MPa; (e) 340 MPa (99% failure load) [16].

A hybrid sensor was also used to detect BVID, which can have a noticeable influence on the mechanical performance of laminates, especially the compressive strength which may decrease by up to 60% compared with an undamaged laminate [17]. A hybrid composite layer composed of a unidirectional ultra-high modulus carbon (YS-90)/epoxy and a S-glass/epoxy material was used. It was applied to detect BVID in a quasi-isotropic $[45/0/90/-45]_{4S}$ laminate fabricated from unidirectional T800 carbon/MTM49-3 epoxy prepreg. Figure 11 shows an example of the impacted-face-, back-face and c-scans for samples subjected to a 12-Joule drop tower test. The c-scan reveals significant delamination damage for all samples, and the delamination size is slightly higher in the original sample compared to the sensor integrated sample. However, there is no change in the appearance of the original sample on either the front or back faces. In contrast, for the sample with the sensor, a visible colour change is observable on both faces. As discussed, these colour changes are due to damage induced in the hybrid sensors. The size of the visible damage area on the front face corresponds to the level of the impact energy.

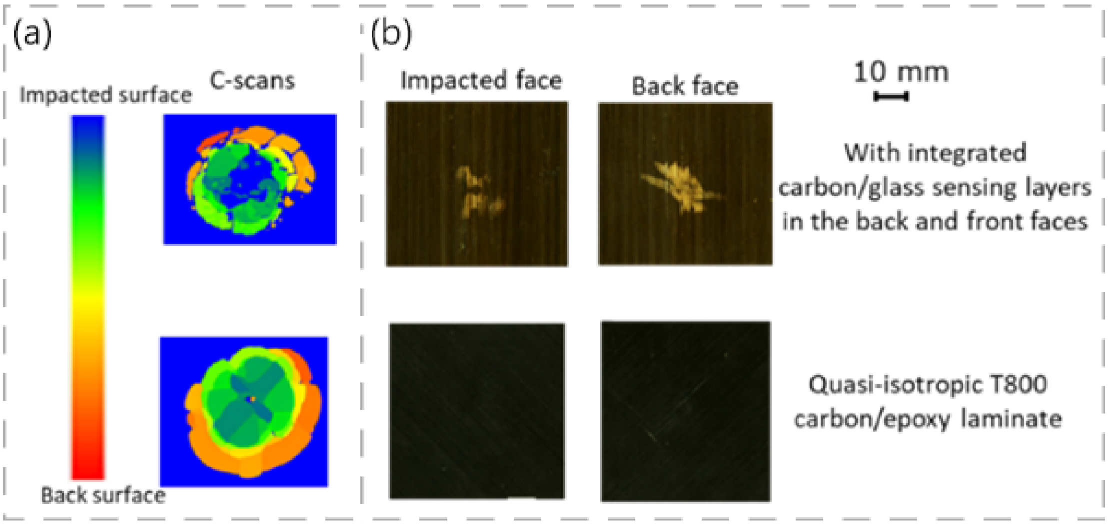

Figure 11. A carbon/epoxy composite (substrate) with integrated impact detector hybrid composite. a) Schematic 3D view, and b) impacted and back faces of specimens with (up) and without (bottom) sensors [18].

A hybrid composite composed of a layer of unidirectional S-glass/epoxy and another layer of unidirectional ultra-high modulus (UHM) carbon/epoxy was used for improving the performance of damaged concrete beams post-retrofitting, to showcase the practical use of mechanochromic composite for both strengthening and structural health monitoring purposes. As depicted in figure 12, when subjected to a strain beyond the strain to failure of the UHM carbon layer, the mechanochromic composite changes its appearance, indicating an overload of the structure.

Figure 12. Colour change in the composite of the retrofitted sample, showing the location and size of the developed underneath cracks [19].

3. Conclusions

The results demonstrated that mechanochromic composites serve as both reinforcement and passively activated, visually readable sensors. The dynamic color change phenomenon provides valuable insights into structural performance, acting as a passive indicator of stress accumulation and potential failure. These glass/carbon hybrid sensors are simple and easy to implement, making them attractive for use in SHM. Practical applications were discussed, including damage monitoring of a bike handlebar and repair of a damaged aluminum panel and a concrete beam. Currently, hybrid composite sensors are developed only for static overload sensing, are not reversible, and are limited to specific strain ranges due to the low strain of carbon fiber. They cannot be fabricated using conventional hand layup or liquid infusion methods because of the thin ply requirement of the sensing layer. Future studies should investigate the performance of purposely pre-damaged sensors in BVID detection to determine precise thresholds for different damage modes, such as delamination and fiber breakage. Additionally, hybrid composite sensors should be tested under various environmental conditions to develop high-performance, function-oriented sensors.

Acknowledgments

The authors acknowledge the funding provided by the UK Engineering and Physical Sciences Research Council (EPSRC) programme Grant EP/V009451/1 on Next generation of high-performance impact resistant composites with visibility of damage.

References

[1] Tabatabaeian, A., Liu, S., Harrison, P., Schlangen, E. and Fotouhi, M., 2022. A review on self-reporting mechanochromic composites: An emerging technology for structural health monitoring. Composites Part A: Applied Science and Manufacturing, 163, p.107236.

[2] Calvino, C., Neumann, L., Weder, C. and Schrettl, S., 2017. Approaches to polymeric mechanochromic materials. Journal of Polymer Science Part A: Polymer Chemistry, 55(4), pp.640-652.

[3] Rev, T., Jalalvand, M., Fuller, J., Wisnom, M.R. and Czél, G., 2019. A simple and robust approach for visual overload indication-UD thin-ply hybrid composite sensors. Composites Part A: Applied Science and Manufacturing, 121, pp.376-385.

[4] Calvino C, Henriet E, Muff LF, Schrettl S, Weder C, Calvino C, et al. Mechanochromic Polymers Based on Microencapsulated Solvatochromic Dyes. Macromol Rapid Commun 2020;41:1900654.

[5] Toivola R, Lai PN, Yang J, Jang SH, Jen AKY, Flinn BD. Mechanochromic fluorescence in epoxy as a detection method for barely visible impact damage in CFRP composites. Compos Sci Technol 2017;139:74–82. https://doi.org/10.1016/j.compscitech.2016.11.026.

[6] de Castro, L.D., Engels, T.A., Oliveira Jr, O.N. and Schenning, A.P., 2024. Sticky Multicolor Mechanochromic Labels. ACS Applied Materials & Interfaces, 16(11), pp.14144-14151.

[7] Tabatabaeian A, Fotouhi S, Harrison P, Fotouhi M. On the Optimal Design of Smart Composite Sensors for Impact Damage Detection. 20th Eur. Conf. Compos. Mater. (ECCM20), Lausanne, Switz., 2022.

[8] Fotouhi, S., Jalalvand, M., Wisnom, M.R. and Fotouhi, M., 2023. Smart hybrid composite sensor technology to enhance the detection of low energy impact damage in composite structures.

Composites Part A: Applied Science and Manufacturing, 172, p.107595.
[9] Jalalvand M, Czél G, Wisnom MR. Damage analysis of pseudo-ductile thin-ply UD hybrid composites - A new analytical method. Compos Part A Appl Sci Manuf 2015;69:83–93. https://doi.org/10.1016/j.compositesa.2014.11.006.
[10] Fotouhi M, Jalalvand M, Wisnom MR. High performance quasi-isotropic thin-ply carbon/glass hybrid composites with pseudo-ductile behaviour in all fibre orientations. Compos Sci Technol 2017;152:101–10.
[11] Czél G, Jalalvand M, Wisnom MR. Design and characterisation of advanced pseudo-ductile unidirectional thin-ply carbon/epoxy–glass/epoxy hybrid composites. Compos Struct 2016;143:362–70. https://doi.org/10.1016/J.COMPSTRUCT.2016.02.010.
[12] Czél G, Wisnom MR. Demonstration of pseudo-ductility in high performance glass/epoxy composites by hybridisation with thin-ply carbon prepreg. Compos Part A Appl Sci Manuf 2013;52:23–30.
[13] Suwarta P, Fotouhi M, Czél G, Longana M, Wisnom MR. Fatigue behaviour of pseudo-ductile unidirectional thin-ply carbon/epoxy-glass/epoxy hybrid composites. Compos Struct 2019;224:110996. https://doi.org/10.1016/j.compstruct.2019.110996.
[14] Fotouhi M, Jalalvand M, Wisnom MR. Notch insensitive orientation-dispersed pseudo-ductile thin-ply carbon/glass hybrid laminates. Compos Part A Appl Sci Manuf 2018;110:29–44. https://doi.org/10.1016/j.compositesa.2018.04.012.
[15] Wilson D. Bicycling science, 3rd edn, 2004.
[16] Jalalvand M, Wu HWML, Sheibanian F, Fotouhi M, Wisnom MR. Self-warning hybrid composite patches for repairing cracked aluminium panels. ECCM 2018 - 18th Eur. Conf. Compos. Mater., 2020, p. 24–8.
[17] Cantwell WJ, Morton J. The impact resistance of composite materials — a review. Composites 1991;22:347–62. https://doi.org/10.1016/0010-4361(91)90549-V.
[18] Fotouhi M, Pui W, Fotouhi S, Jalalvand M, Wisnom MR. Detection of Barely Visible Impact Damage Using a Smart Hybrid Composite Surface Layer. Twenty-Third Int. Conf. Compos. Mater., Belfast: 2021.
[19] Fathi A, Mohammadi R, Schlangen E, Fotouhi M, Flexural Performance of Damaged Concrete Prisms Retrofitted Using Mechanochromic Glass/Carbon Hybrid Composites, Concreep12 conference, June 5 –7, 20244.