Tabatabaeian, A., Fotouhi, S., Harrison, P. and Fotouhi, M. (2022) On the Optimal Design of Smart Composite Sensors for Impact Damage Detection. In: 20th European Conference on Composite Materials (ECCM20), Lausanne, Switzerland, 26-30 Jun 2022, (Accepted for Publication).

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ON THE OPTIMAL DESIGN OF SMART COMPOSITE SENSORS FOR IMPACT DAMAGE DETECTION

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Abstract: *This paper aims to study the feasibility of smart thin-ply hybrid glass/carbon sensors in quasi-static impact damage detection and analyse different design strategies to achieve an optimal sensor performance. A set of carbon fibre reinforced polymer (CFRP) specimens was manufactured, and the hybrid sensing layers were attached and evaluated. New architectures of hybrid sensing layers are proposed using woven prepregs and introducing pre-cuts to increase stress concentration. The sensors are used under indentation to detect the damage. Outcomes established key design insights, which will be used further in developing the self-sensing technology and may result in more sustainable composite structures that are light-weight, easy to inspect and last longer.*

Keywords: Self-sensing; Composite materials; Structural health monitoring

1. Introduction

Fibre reinforced polymer (FRP) composites are vastly applied in different sectors such as aerospace, automotive, wind turbine and civil engineering industries. Despite having several advantages over conventional engineering materials, there is still room for improving FRP composites, for example, developing new structural health monitoring (SHM) techniques to study their damage evolution and potentially enhance their failure mechanisms to avoid unexpected fracture or failure.

The damage detection using smart thin-ply hybrid glass/carbon composite sensors is a new chapter in SHM of composite structures, inspired by some early studies on the pseudo-ductile hybrid (PDH) composites [1-3]. PDH composites have recently been introduced as a new generation of FRP composites to address sudden and unexpected failure. When demonstrating pseudo-ductile behaviour in thin interlayer glass/carbon-epoxy hybrid composites, a pattern was observed by Czél and Wisnom [3] during the gradual failure of the specimens. The translucent nature of the constituent glass-epoxy layers made delamination detection possible to the naked eye. It was realised that this could be used for sensing damage on the surface of a structure, offering the potential for safer operation in service. This SHM technology is lightweight, bio-inspired, and wireless and has mainly been investigated in tensile loading [4].

This paper explores the feasibility of hybrid glass/carbon sensors in damage detection, specifically for FRP composite structures under indentation (quasi-static impact) loading conditions. To this end, after demonstrating the applicability of the sensing system to detect indentation damage, we made some developments in the design of the sensor: a) the unidirectional (UD) glass layer was replaced by a woven glass layer, and b) the influence of discontinuity in the sensor, in the form of pre-existed cuts, was studied. The results highlighted that woven glass can be a good alternative to UD glass, and the sensor activation threshold can be well set at a desired load level by applying cuts in carbon layer.

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2. Experimental procedure

2.1 Design concept

The design concept is based on the change in the appearance of a hybrid glass/carbon sensor when loaded beyond a predefined strain. The sensor is on the component's surface and experiences similar strains as the material beneath. It consists of a 'sensing' layer (carbon layer) and an outermost layer (glass layer). The intact carbon layer absorbs the light through the translucent glass layer showing a dark appearance. After the strain exceeds the failure strain of the carbon layer, the carbon layer develops multiple fractures, and the light is reflected from the interfacial damaged glass/carbon are around the carbon layer fractures, demonstrating light stripes. The visible interfacial damage is caused by the fragmentation of the carbon fibre sensing layer followed by stable, dispersed delamination [5]. The schematic of the sensor-set up and its attachment to a substrate material is shown in Figure 1.

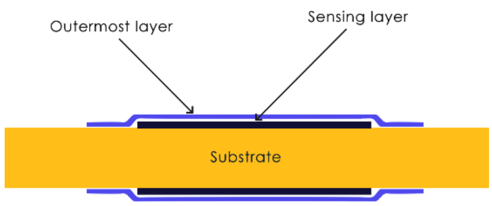

Figure 1. Schematic of hybrid thin-ply composite sensors attached to a substrate material

Various parameters can influence the design of the proposed hybrid composite sensors. Their geometry (length and width) can be varied as well as the stiffness ratio of the sensor to the substrate by either changing the thickness of the layers or by utilising different composite prepreg materials. This technology is an ongoing field in SHM of composites, and there is still much room for improvement, particularly in developing new designs for the thin-ply hybrid composite sensors to monitor low velocity impact and indentation damages.

2.2 Materials and manufacturing

Unidirectional IM7 carbon/913 epoxy prepreg supplied by Hexcel was used to fabricate the reference laminate with standard dimensions based on the ASTM D7136-07 (100 mm*150 mm). Two types of hybrid sensors, made from UD glass/YS 90A carbon and woven glass/YS 90A carbon with the same size as the reference laminates, were integrated into the front and back face of the laminates and cured at the same time as the core laminate. The core laminate was laid up in a quasi-isotropic $[+45/0/90/-45]_{4s}$ stacking sequence where 0 is the direction of unidirectional fibre orientation parallel to the long side of the plate. The sensors were composed of a single layer of the YS 90A carbon prepreg, with 90 orientation, sandwiched between the core laminate and a single layer of a glass prepreg with 90 orientation (Figure 2). It should also be noted that the total thickness of the sensor integrated specimens was 4.65 mm and 4.50 mm for specimens with UD and woven glass layers, respectively.

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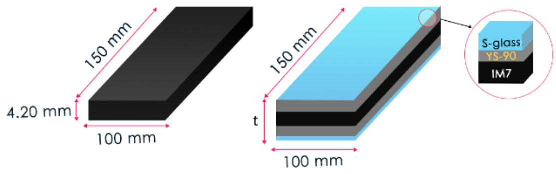

Figure 2. Schematic of the reference and sensor integrated specimens

In order to investigate the feasibility of the proposed sensing system, two sets of samples, with and without the sensor, were manufactured. Also, two other sets of sensor integrated samples was manufactured in which: an array of cuts was made in the sensing layer (carbon layer) using a V-shape blade (Figure 3) [6] in one group, and UD glass was replaced by woven glass layer in another group. Each coupon test was repeated three times, and the average amounts are reported in this paper. A schematic of different specimen groups manufactured in this study is represented in Figure 4.

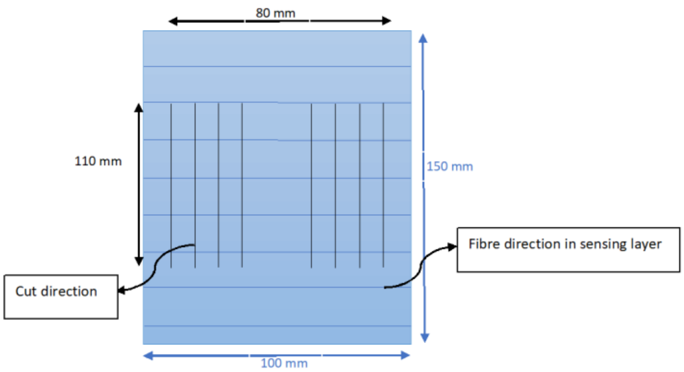

Figure 3. The cut pattern for the carbon layers of the discontinuous hybrid composite plates

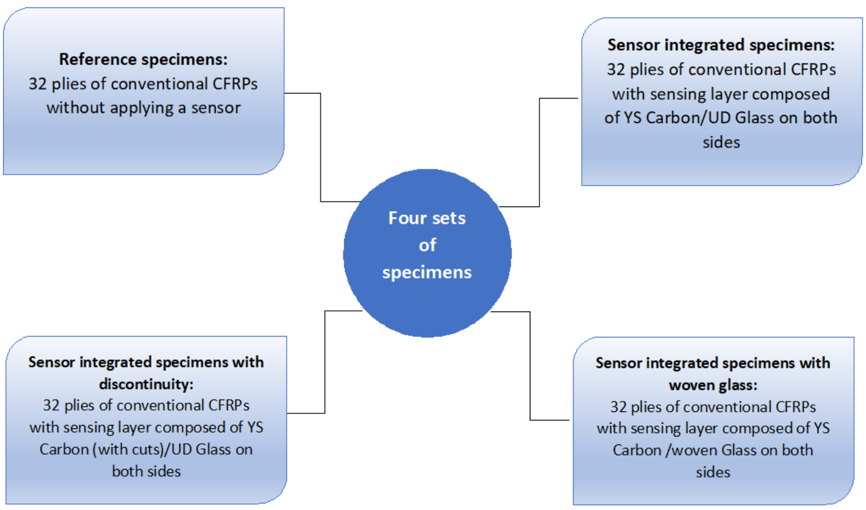

Figure 4. Different sets of manufactured specimens in this study

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2.3 Indentation tests

In some cases, static indentation tests can be a suitable substitute for low velocity impact tests of laminated composite materials [7]. A Zwick 250 machine was used to perform indentation tests. The tests were carried out by mounting a 16 mm diameter steel indenter with the 150 mm*100 mm specimens simply supported on a 125 mm* 75 mm window and clamped lightly to it using four rubber-tipped clamps (Figure 5). The tests were conducted in controlled conditions imposing a displacement rate of 2 mm/min. Videos were also taken from both the front and back faces of the specimens during the test and related to different stages of the sensor activation.

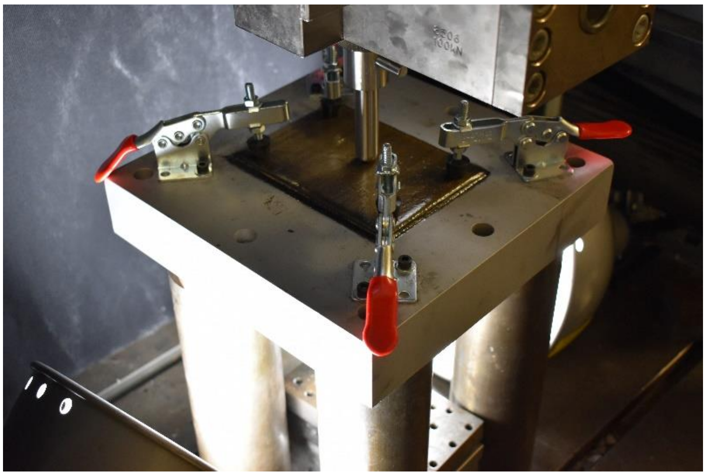

Figure 5. Experimental configuration for the static indentation tests

3. Results and discussion

3.1. Quasi-static impact behavior

The results of the indentation (quasi-static impact) tests of all four sets of specimens are shown in Figure 6. In all graphs, there are two major drops associated with the initiation and development of the damage in the form of delamination, where before the first drop, elastic behavior is observed. All the tests were continued until the force level of 12 KN, in which two main drops happened, but no fibre fracture was seen. A comparison of the four graphs indicates that integrating the sensors does not cause a significant difference in the force-displacement behavior of the CFRP composites under indentation loading. However, the reference specimen experienced a slightly higher deformation after the load drop compared to the sensor integrated specimens.

The results also clarify that the specimens equipped with woven glass in their sensing layer would undergo a higher deformation level under the same force value than samples with the UD glass layer, particularly after the first load drop. Moreover, a different force-deformation response is seen in specimens with woven glass layer after the second load drop, where multiple subsequent drops are observed. The force-deformation response provided by these graphs would help in the optimal designing of hybrid glass/carbon sensors by calculating the desired strain levels for sensor activation. This can also help determine the required critical energy level to induce delamination damage in drop-weight impact tests, as suggested in [7].

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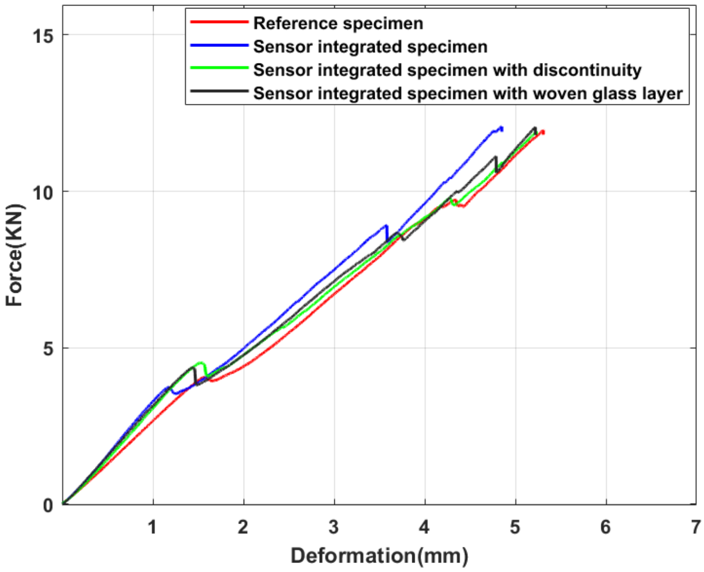

Figure 6. Quasi-static impact behavior of different sets of specimens

3.2. Sensor activation and visual observations

The specimens' back and front faces were monitored during the tests, and videos were taken from both sides to evaluate the sensor activation process. The time of each video was then related to the force-time graphs obtained by the indentation machine software. The load level at which sensor was activated is illustrated in Figure 7. In all three groups, the back face sensor was activated sooner than the front face one. Also, in all samples, the back and front face sensors were activated before the first and second load drops, respectively, which are way before the final fibre fracture.

As shown by Figure 7(b), sensor activation on two sides of the specimens happened at a lower force level compared to Figure 7 (a), especially in the front face, where the required force to activate the sensor has decreased from nearly 6.5 KN in intact specimens to 5 KN in specimens with discontinuities in their sensing layer, suggesting that initiation of the impact-induced delamination can be controlled by causing some discontinuities in the form of cuts.

Figure 7(c) demonstrates the required force level for sensor activation in the back and front faces of the specimens with the woven glass in their sensing layer. The load value for sensor activation in the back face is slightly higher than that of samples with the UD glass, while in the front face, sensors with the woven glass were activated at a lower force level. This suggests that the damage in the back face is due to tension and is dominated by the fibre properties, whereas for the front face, delamination damage is active. The earlier delamination damage in the woven is due to lower toughness of the woven glass prepreg compared with the UD glass that is an aerospace grade prepreg. A similar behavior was observed comparing the UD glass samples with and without discontinuities, where there is almost no difference between the damage in the back face initiation time, whereas the front face damage was initiated earlier for the sample with discontinuities due to the lower critical energy required for delamination initiation.

Figure 8 shows the back and front faces of the specimens after the quasi-static impact tests. It is seen that while there is no visible sign of damage in reference samples (Figure 8(a)), it can be

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clearly observed in all sensor integrated specimens, and this is more visible in the back face. No significant difference can be seen in sensors with and without discontinuities (Figures 8(b) and 8(c)), but the specimens with woven glass have a different appearance after the test. Given the thinner thickness of the sensors with a woven glass layer and their required activation load, they could potentially be a good alternative to UD glass layers in particular applications where the use of woven glass is advantageous.

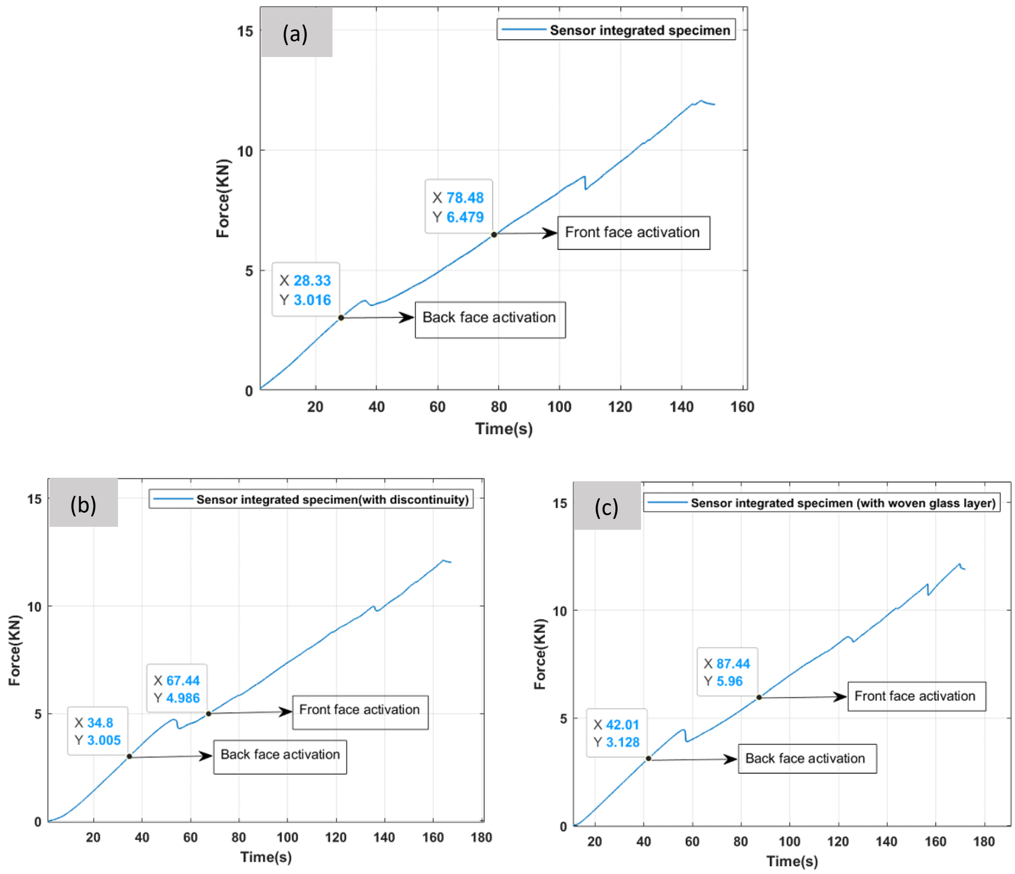

Figure 7. Sensor activation during quasi-static impact tests on the front face and back face of the samples

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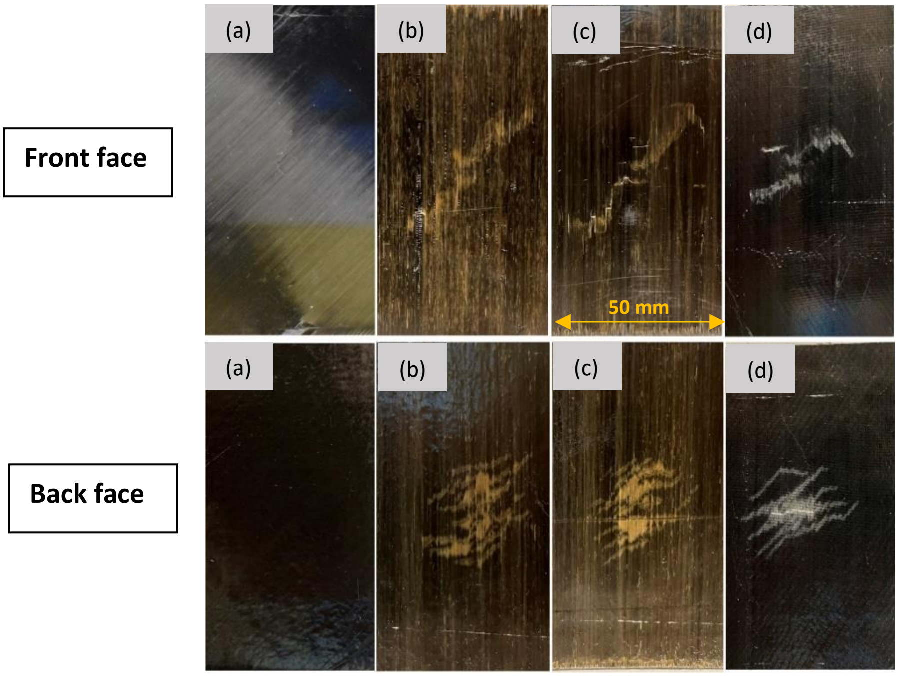

Figure 8. Visual observation of damage after quasi-static impact on the front face and back face of the samples: a) reference, b) with sensor (UD glass), c) with sensor (UD glass and discontinuity in carbon layer), d) with sensor (woven glass)

4. Conclusions

This paper explored the possibility of applying hybrid glass/carbon sensors on composite structures to monitor the quasi-static impact damage. Four different sets of specimens were manufactured, including reference samples (without sensor), sensor integrated samples with UD glass layer and without discontinuity, sensor integrated samples with UD glass layer and with discontinuity (in carbon layer), and sensor integrated samples with woven glass layer and without discontinuity. The feasibility of the proposed sensing technology and the influence of materials and pre-damages in the sensing layer were investigated experimentally. The results indicated that quasi-static impact damage could be well detected using hybrid thin-ply glass/carbon sensors, while they do not cause a significant difference in structural properties of the composites. It was seen that back and front face sensors are activated before the first and second load drop, respectively, which are way before the final fibre fracture. It was observed that the dominant front face damage in the sensor is delamination, whereas fibre properties are governing the back face damage.

The outcomes also suggested that initiation of the quasi-static impact-induced delamination can be well controlled by causing some discontinuities in the form of cuts. Another conclusion was that woven glass could potentially be a good alternative to UD glass in the sensing layer. The results of this work can be used in future research activities for optimal designing of self-sensing composites structures to trigger specific damage mechanisms under low-velocity impact loading conditions.

Acknowledgements

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This work was funded under the UK Engineering and Physical Sciences Research Council (EPSRC) Grant EP/V009451/1 on Next generation of high-performance impact resistant composites with visibility of damage. The data necessary to support the conclusions are included in the paper.

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