Visualization of fatigue load cycle numbers using a glass/carbon hybrid composite sensor

Mahmoudi, Ali; Acosta, J. David; Jalalvand, Meisam; Fotouhi, Mohammad; Wisnom, Michael R.; Khonsari, Michael M.

DOI
10.1016/j.sna.2024.115551

Publication date
2024

Document Version
Final published version

Published in
Sensors and Actuators A: Physical

Sensors & Actuators: A. Physical 376 (2024) 115551

Contents lists available at ScienceDirect

Sensors and Actuators: A. Physical

journal homepage: www.journals.elsevier.com/sensors-and-actuators-a-physical

Visualization of fatigue load cycle numbers using a glass/carbon hybrid composite sensor

Ali Mahmoudi [a], J. David Acosta [b], Meisam Jalalvand [b], Mohammad Fotouhi [c], Michael R. Wisnom [d], Michael.M. Khonsari [a,*]

[a] *Department of Mechanical and Industrial Engineering, Louisiana State University, Baton Rouge, LA 70803, USA*
[b] *Engineering Materials, School of Engineering, University of Southampton, Southampton SO17 1BJ, UK*
[c] *Department of Materials, Mechanics, Management and Design, Delft University of Technology, Delft, Netherlands*
[d] *Bristol Composites Institute, University of Bristol, Queen's Building, University Walk, Bristol BS8 1TR, UK*

ARTICLE INFO

Keywords:
Fatigue
Delamination
Hybrid composites
Laminate
Structural health monitoring

ABSTRACT

A sensor for visualizing the fatigue load cycles was designed, fabricated, and tested. The sensor is made of a glass/carbon hybrid composite and utilizes the delamination length at the glass/carbon interface as an indicator for fatigue cycles. Appropriate design parameters were obtained by performing finite element analysis on the delamination development at the interface between the glass and carbon layers. Hybrid sensors with different carbon layer thicknesses were manufactured, attached to glass/epoxy substrates, and tested under fatigue loading. The predicted results based on the Paris law for crack extensions in one configuration are compared with the experiments for a different configuration to illustrate the efficacy of the approach.

1. Introduction

The superior strength and low density of composite materials are among the key parameters that outperform traditional metals, particularly in applications where consideration of weight is crucial. Yet, while composites offer many desirable properties, the prediction of their behavior in applications involving cyclic fatigue is far more challenging than their metal counterparts. While several models have been established to predict the fatigue behavior of composite materials, the complexities associated with the failure modes render their applicability to very specific types of loading and a limited range of operating conditions [1]. A particularly challenging problem in the operation and testing of composite stems from difficulties in detecting internal fatigue damage—from micro-transverse cracks to substantial delamination—that often results in sudden failure with no warning [2]. As a result, the safety and damage tolerance of current composite structures is heavily based on conservative design limits that mask the true weight-saving potential of advanced composites [3]. The ability to detect the fatigue loading that a structure has been subjected to would be a big step forward in health monitoring and prognosis.

In general, structural integrity is assessed either through periodic inspections using interruptive Non-Destructive Evaluation (NDE) methods or through continuous in-service Structural Health Monitoring (SHM) [4]. These are discussed in recent review papers [4–7]. NDE and SHM analyses have evolved into indispensable parts of many critical systems by facilitating the early detection of defects, monitoring structural health, and ultimately contributing to enhanced operational efficiency and the prevention of catastrophic failures. These technologies play a pivotal role in ensuring the safety and reliability of these vital infrastructures encompassing transportation [8–11], energy production [12], and industrial facilities [13,14].

Eddy current, ultrasonic inspection, vibration-based methods, and imaging techniques such as infrared thermography and X-ray radiography are some of the common types of NDE techniques [15,16]. These methods are often labor-intensive and may require disassembly of the structure, leading to significant out-of-service time periods [17]. This means that advanced lightweight composite structures need to be frequently taken out of service for offline condition assessments [18]. On-board SHM technologies can potentially allow for periodic or continuous examination, even while the structure is in service so they can reduce the downtime and offer significant benefits. However, the real-time health monitoring of composite structures undergoing cyclic loading has been proven to be a challenge.

SHM relies on sensors that can be permanently placed on the

* Corresponding author.
E-mail address: khonsari@lsu.edu (Michael.M. Khonsari).

https://doi.org/10.1016/j.sna.2024.115551
Received 8 February 2024; Received in revised form 11 May 2024; Accepted 4 June 2024
Available online 6 June 2024

structure to monitor certain parameters over the lifetime of the components. Instrumentation of structures with electronic sensors connected using a vast network of wires tends to be heavier and often requires bulky accessories. Some sensors, such as the conventional resistance strain gauges, fiber-optic, and piezoelectric sensors, are often the first choice in many applications at the expense of post-processing [19]. There is a significant amount of information to analyze to determine if the combination of signals received can be interpreted as a damage development. A review of various methods that have been explored is presented in [20]. However, most of these are proven to be too complicated and time-consuming, requiring special apparatus and highly trained human operators and changing the mechanical properties by adding weight [21]. Although some fatigue sensors are devised and manufactured for monitoring the fatigue behavior of structures [22,23], no SHM technique has been successfully used for weight-sensitive applications in composite structures [24].

Self-sensing composites, a burgeoning field in SHM, have emerged to visually represent their mechanical and physical conditions, including damage, stress, strain, etc. [25]. The electrical resistance change method is used for monitoring the delamination of CFRP laminates [26] and matrix cracking [27]. The change in conductivity of polymer composites and nanocomposites is employed to investigate strain and damage evolution within the material [28]. Utilizing thin interlayer glass/carbon hybrid composites proves beneficial in visualizing delamination due to the translucent nature of the glass layer [29]. Hybrid fiber-reinforced polymers are applied for self-monitoring deformation and damage in concrete [30]. Moreover, glass/carbon hybrid composites have been developed as indicators of load thresholds [31] and overload sensors [32].

This paper presents a new sensor/indicator for constant amplitude fatigue load based on glass/carbon hybrid composites to indicate the number of fatigue cycles applied to a substrate. Different sensor attachment methods to the substrate are discussed, and the Finite Element (FE) method is used for their assessment. Finally, two sensors with different configurations are manufactured and experimentally tested. The promising results prove the concept and offer a viable means to monitor the number of constant-amplitude fatigue cycles applied to a structure. Furthermore, these findings indicate the potential for the development of this sensor-based approach as an SHM technique for evaluating damage resulting from fatigue loading in a substructure.

2. Concept of hybrid sensors

2.1. Over-load sensor for static applications

Recently, glass/carbon hybrid composites have been used as non-electronic visual sensors to detect tensile quasi-static overloads applied to a substrate [32]. Fig. 1(a) shows a schematic and real top-view picture of the glass/carbon hybrid composites before any overload. The translucent glass layer allows the light to pass through to be absorbed by the carbon layer. As a result, the glass/carbon hybrid is seen as black before any overload is applied. Fig. 1(b) shows a schematic and a top-view picture of the same hybrid after being exposed to an overload that has generated multiple fractures in the carbon layer, followed by dispersed delamination at the glass/carbon interface. The newly generated air gap/interface reflects a significantly large portion of incident light; therefore, the delaminated areas are seen with a brighter color, resulting in a stripe pattern. Fig. 1(c) shows an overload sensor attached to a bike's handlebar. The stripe pattern visually shows that the handlebar has been overloaded.

Additionally, fatigue tests on the same type of glass/carbon hybrid composites have shown that if the tensile load causes longitudinal fracture in the carbon layer, the following fatigue cycles will lead to a delamination propagation with a steady delamination growth rate between the glass and carbon layer which will be detectable by naked eyes [33,34].

2.2. Visual sensor for cyclic fatigue

Similar to the quasi-static overload sensor presented in [32], the sensor has a carbon layer sandwiched by translucent glass layers, but instead of relying on the fracture of the carbon layer for the sensing mechanism, a cut is introduced within the carbon layer that causes interlaminar shear stresses between the glass and carbon layers at the cut tip, leading to gradual degradation and delamination of the interface due to cyclic fatigue loads. Fig. 2 shows a schematic of the glass/carbon fatigue cycle indicator and the hypothetical fatigue response that might be achieved at different numbers of fatigue cycles, indicated by 0 k, 50 k, 100 k, and 150 k.

The presence of delamination in the sensor detectable by the naked eye indicates fatigue-induced degradation, allowing for a correlation to be established with the number of fatigue cycles and delamination length in the attached sensor. Analyzing the length of delamination in the sensor provides a valuable means to estimate key parameters such as the number of cycles in a constant-amplitude loading scenario. For more generic loading cases, i.e., variable amplitude loading scenarios, the delaminated length could be potentially linked to equivalent hours of operation or consumed lifetime. All these can help to estimate the extent of damage or residual stiffness and strength in a substrate.

The fatigue experiments presented in [33] on glass/carbon hybrid composites showed that after the initiation of carbon layer fragmentation, delamination propagates fairly equally at both carbon/glass interfaces perpendicular to the mid-plane. This means that the change in appearance of the samples is more or less the same on both sides.

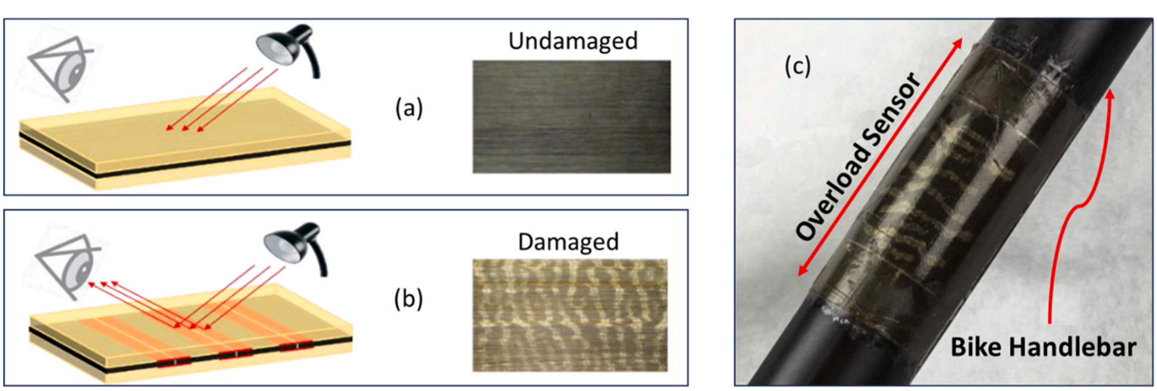

Fig. 1. Working principles of the hybrid composite strain overload sensors: (a) intact carbon layer absorbs light at glass/carbon interface and (b) striped pattern becomes visible due to light being reflected from locally damaged glass/carbon interface around the sensing layer crack; (c) bike handlebar fitted with overload sensor [32].

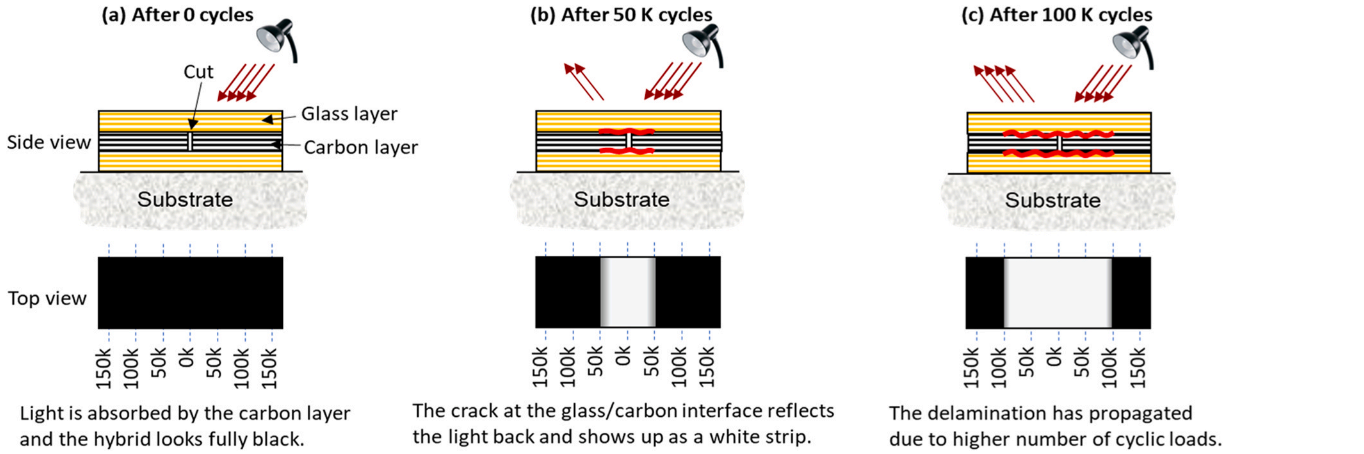

Fig. 2. Schematic of the glass/carbon hybrid fatigue cycle indicator with central cut carbon layers after (a) 0 cycles, (b) 50 k cycles, and (c) 100 k cycles.

However, a hybrid sensor with a centrally cut carbon layer bonded to a thick substrate does not satisfy the symmetric conditions and therefore, propagation of delamination at the two interfaces on either side of the carbon layer is not guaranteed. To address this concern, two different sensor attachment methods to the substrate are examined to determine the optimum design: 1) Fully attached sensors to the substrate and 2) Partially end attached sensors to the substrate. The details of these configurations are presented in the next section. Sensor attachment method #1 is probably the most obvious and schematically shown in Fig. 2. As discussed in the next section, the proposed sensor attachment method #2 can generate a symmetric delamination propagation for both the top and bottom interfaces between the carbon and glass layers of the fatigue indicator. Therefore, the delamination on either side of the cut carbon layer is identical. The effect of the attachment method is studied and fatigue sensors are designed for experimental testing in the following part.

3. FEA and sensor design

Finite element analysis is used to investigate the effect of the attachment method and design parameters on the sensor's function. Both attachment methods #1 and #2 are modeled and the design parameters investigated in this study are the length of the bond between the sensor and substrate, fiber orientation of glass layers in the sensor, and thickness of the carbon layer in the sensor. A schematic design of a sensor attached to a substrate is shown in Fig. 3. The hybrid laminated sensor has a glass/carbon/glass lay-up, with the central carbon layers cut before the manufacturing process during the lay-up stage. The substrate can be any material but for this paper, we have used S-glass/epoxy composites.

FE modeling and the Virtual Crack Closure Technique (VCCT) [35] are utilized within the Abaqus software to obtain the strain energy release rate (G_{II}) at the crack tips at the glass/carbon interfaces. It is worth mentioning that in this study, the values of G_I were also initially calculated for a few cases, including those with crack lengths of 2 mm and 10 mm. However, these values were determined to be insignificantly small, effectively approaching zero. Consequently, only G_{II} values are presented in this paper. For reference, the average G_{II} value at the crack tip of a 2 mm crack is 0.61 N/mm, while the corresponding G_I value for the same case is only 8×10^{-16} N/mm, probably coming from the round-off errors of the numerical functions. Hence, it's reasonable to assume pure mode II behavior. A 3D model employing linear hexahedron elements (C3D8) is utilized in this analysis. The element size is set at 0.5 mm in both the longitudinal and transverse directions, and each prepreg layer is meshed with one element. The bonded regions for partially and fully attached sensors in the FE model are depicted in Fig. 4. A constant load is applied to the substrate ends to evaluate the strain energy release rates. The loading generates a small amount of bending, but the effects were found to be negligible. Interlaminar shear stresses (τ_{xz}) and strain energy release rate for crack propagation (G_{II}) with an initial crack length are recalculated by changing the design variables. As the design is symmetric with respect to the central cut plane in the carbon layer, only half of the sensor and substrate are modeled, as shown in Fig. 4. Bonding a sensor on top of the substrate leads to a small offset in the center-line of the substrate at areas with and without the sensor. This offset theoretically can cause a small bending and out-of-plane curvature, but due to the high flexural stiffness of the substrate, such out-of-plane curvature is negligible and is not assessed in this paper. The top and bottom glass layers are composed of 2 standard-thickness plies each. The carbon sensing layer is fabricated using 5 thin plies to explore the impact of bonding methods and the orientation of glass layers. Additionally, a model with a 3-ply carbon layer is employed to examine the effect of carbon layer thickness. The substrate, on the other hand, comprises a 10-ply glass layer. Detailed dimensions for both the substrate and the sensor can be found in Fig. 4, and the material properties are provided in Table 1 at a later point in

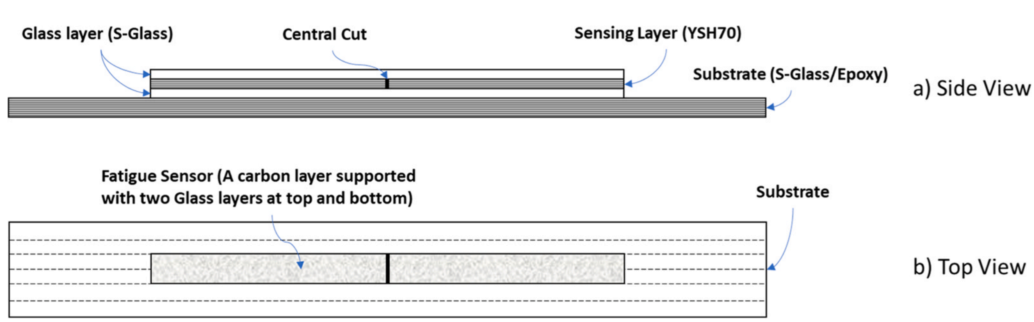

Fig. 3. Schematic of fatigue life sensor: a) Side view and b) Top view.

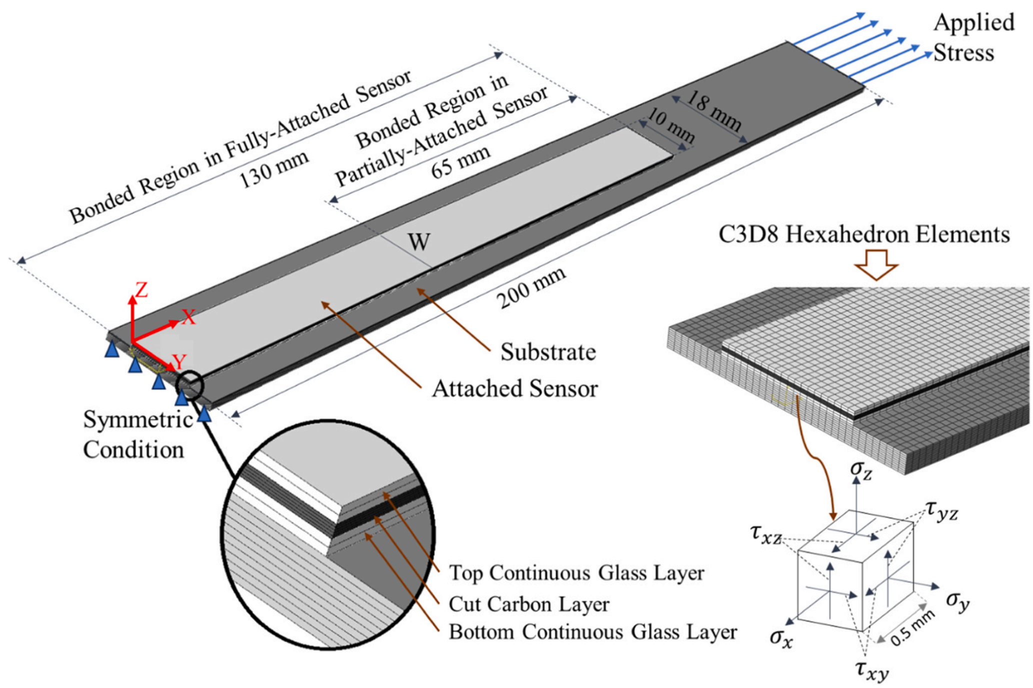

Fig. 4. Half-modeling of the sensor and the substrate for FEA analysis in Abaqus software.

Table 1
Properties of the applied materials.

Prepreg type	YSH70/Epoxy[a]	S-glass/913 Epoxy[b]
Fiber modulus [GPa]	720	88
Fiber failure strain [%]	0.5	5.5
Longitudinal modulus, E_{11} [GPa]	430	45.6
Transverse modulus, E_{22} [GPa]	6.2	-
Strain to failure [%]	0.4	3.9
Cured nominal thickness [mm]	0.04	0.155
Fiber areal weight [g/m^2]	30	190
Fiber volume fraction [%]	60	51

[a] Based on the manufacturer's YSH70/epoxy dataset.
[b] Based on the manufacturer's S-glass/913.

Section 3.

3.1. Effect of the bonding method (partially versus fully bonded)

Two different designs of fully-attached and partially-attached sensors are studied, and the interlaminar shear stresses and strain energy release rate are compared for initial uniform delamination of 2 mm across the width at both top and bottom interfaces. In the fully attached sensor design, the bottom glass layer is bonded to the substrate throughout the whole length. However, in the partially attached sensor, only half of the sensor length at both ends is attached to the substrate. Although stress singularities occur at the crack tip, and the results exhibit sensitivity to mesh refinement, a qualitative comparison can still provide valuable insights. A tensile force of 6.8 kN is applied to the substrate end to assess the sensor's performance. This corresponds to an average tensile stress of 150 MPa in the substrate. Fig. 5 shows the interlaminar shear stresses for these two designs along the pre-delaminated crack tips at the top and bottom of the carbon layer. Top and bottom cracks refer to delamination between the carbon and top and bottom glass layers. The average magnitude of interlaminar shear stresses shown with a dotted line for the fully attached sensor at the top and bottom cracks are 88 MPa and 70 MPa, while that is 107 MPa at both the top and the bottom cracks for the partially attached sensor design. This indicates that the partially attached sensor can lead to more uniform shear stress distribution at the top and bottom interfaces. However, the fully attached sensor shows higher shear stresses at the bottom interface than the top one, indicating that there are non-uniform conditions at the top and bottom interfaces.

Fig. 6 presents similar results by showing the strain energy release rate (G_{II}) at the top and bottom interfaces for each design. For the fully attached design, the average values of G_{II} in the width direction are 0.26 N/mm and 0.36 N/mm for the top and bottom interface of glass and carbon layers. This means the delamination growth at the bottom crack is faster than at the top crack. This is particularly undesirable as

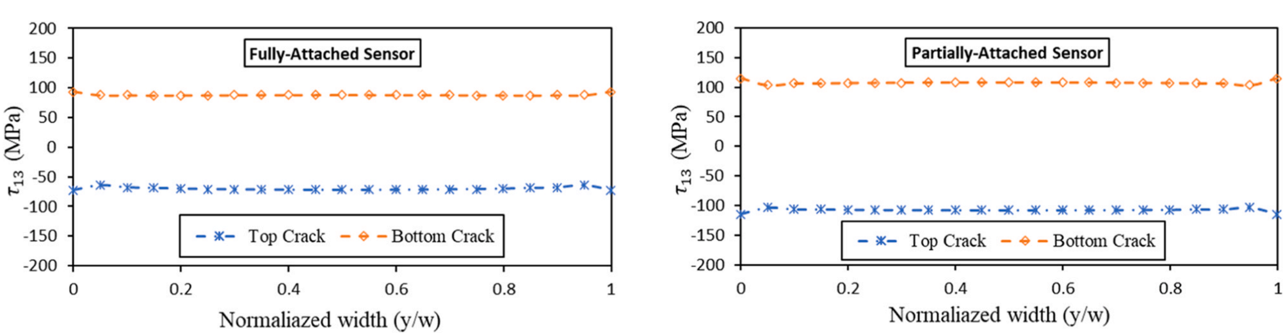

Fig. 5. Interlaminar shear stress at the tip of 2 mm pre-crack in different designs: a) fully attached and b) partially attached sensors.

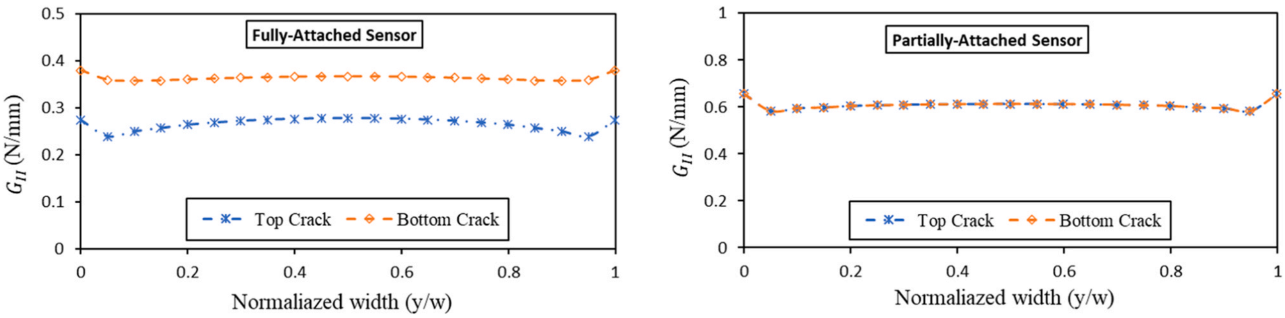

Fig. 6. Strain energy release rate at the tip of 2 mm pre-crack in different designs: a) fully attached and b) partially attached sensors.

the bottom interface is not visible since it is covered by a black carbon layer above it. On the other hand, the average value of G_{II} at both top and bottom interfaces for a partially attached design is 0.60 N/mm, which leads to an equal delamination growth. This becomes important, especially when noting that the bottom interface is not visible by the naked eye as it is covered by the carbon layer, and the sensing mechanism is intrinsically based on the delamination propagation at the top interface. Therefore, if delamination at the top and bottom surfaces is not growing equally, it is important to know the effect of the bottom interface delamination on the top interface delamination. These results suggest that the partially-attached sensor yields symmetric crack propagation in contrast to the asymmetric crack propagation observed in fully-attached sensor configurations.

3.2. Effect of fiber orientation of sensor's glass layers

As demonstrated in the preceding section, a partially attached design results in more similar strain energy release rates at the top and bottom crack surfaces. Hence, a partially bonded design is selected in this section to investigate the effect of fiber orientation. The fiber orientation in the carbon layers is chosen to be 0° to maximize the stiffness of the sensing layer along the loading direction which leads to an increase in the energy release rate at the glass/carbon interface. The glass layer's fiber orientation (θ) can significantly affect the stiffness of the glass layer and consequently strain energy release rate at the crack tip, which can be used as a designing parameter for sensor applications. Maintaining the balanced symmetric condition of the hybrid sensor requires the use of +θ/- θ angle-ply glass lay-up for the top and -θ/+θ for the bottom glass layers. Fig. 7 compares the G_{II} results for glass layer fiber orientations of 0°, 45°, and 90° along the width of the fatigue sensor. The higher values of the G_{II} near the free edges result from edge effects. This shows that the edge effect is more pronounced for θ = 45° fiber orientation, which can result in non-uniform delamination propagation along the width, e.g., faster crack extension at the edges of the sensor. Hence, off-axis laminates exhibit an unfavorable mode of crack propagation along their edges due to the influence of the free edge effect. This presence of off-axis layers may lead to delamination between the glass and sensing layers or matrix cracking within the glass layers. Moreover,

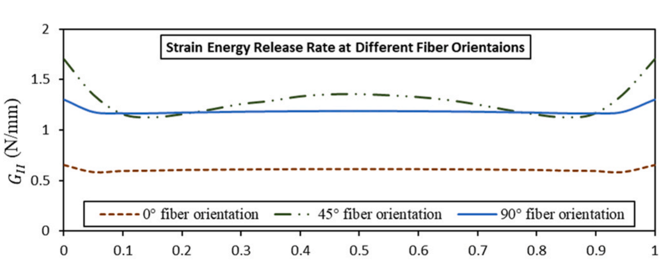

Fig. 7. Comparing the strain energy release rate results at the tip of 2 mm pre-crack at different fiber orientations under a maximum load of 6.8 kN.

the strain energy release rate rises as θ increases from 0° to 45° or 90°, attributed to a decrease in glass layer stiffness. Analytical results show that a reduction in the stiffness of the continuous glass layer results in an increase in the strain energy release rate in hybrid glass/carbon laminates [36]. Fig. 7 shows that the fiber orientation of the glass layer can be utilized to control the delamination propagation rate in the design process to reach the desirable delamination growth. The 0° glass fiber orientation leads to a more uniform energy release rate and consequently, a more uniform crack extension in the width direction. This is more desirable as makes it easier to read the sensor. Also, there is no risk of matrix cracking due to loads along the sensor length direction in a 0° glass layer. Therefore, 0° glass has been chosen in this study as the orientation of glass layers.

3.3. Effect of carbon layer thickness

Carbon layer thickness or the number of carbon laminae used in the carbon layer block affects the strain energy release rate and, consequently, the delamination growth of the sensing layer in a hybrid sensor. This study explores two distinct carbon thickness options for the hybrid sensor design in a partially attached sensor. One features a 5-ply carbon layer with a thickness of 0.25 mm, while the other incorporates a 3-ply carbon layer with a thickness of 0.15 mm. Fig. 8 illustrates the variations in the average strain energy release rate at the tip of 2 mm pre-crack across various delamination lengths with a logarithmic scale for two different carbon-layer thicknesses. A higher number of laminae in the carbon layer results in a higher strain energy release rate. This means that by increasing the thickness of the carbon layer, the crack growth rate increases, which can be used as a parameter in the design process to control the delamination of the sensor. Also, as the crack length increases, there is a consistent reduction in the strain energy release rate for both design configurations and carbon layer thicknesses. This observation highlights the inverse relationship between crack length and strain energy release rate, which should be considered in the design

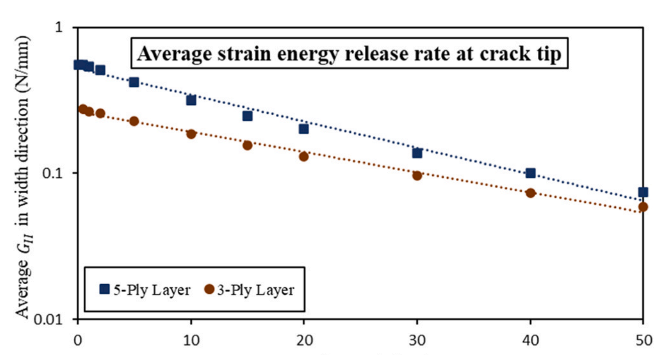

Fig. 8. Strain energy release rate at the tip of 2 mm pre-crack for different carbon layer thicknesses in partially attached sensors under a maximum load of 6.8 kN.

and manufacturing of sensors. The obtained results in Fig. 8 show a good linear correlation when the vertical axis, the energy release rate values, are plotted on a logarithmic scale. This can be used to simplify the relationship between G_{II} and crack length and helps the crack propagation predictions needed in the design of the sensor for a wide range of numbers of cycles.

4. Materials, manufacturing, and experiments

This section explains the experimental procedure to demonstrate the concept of the fatigue sensor explained above. Sensor is suitable for a wide range of substrates and there are some options for selecting the materials for the carbon layer. The strain to failure of the sensing carbon fibers must be higher than the maximum tensile strain applied to the substrate to avoid fracture of the sensing carbon layer. To keep the thickness of the sensing layer low, high-modulus carbon fiber layers can be used depending on the desired strain.

4.1. Materials and specimen design

In this study, the maximum tensile strain of 0.3 % is selected for the fatigue load. UD S-glass/epoxy prepreg supplied by Hexcel was selected as the outer and translucent layer material. Thin-ply YSH70/epoxy carbon prepreg produced by North Thin Ply Technology (NTPT) was selected for the sensing layer. This carbon layer provides a significant modulus of 430 GPa with a failure strain of 0.4 % which is above the 0.3 % maximum tensile strain in each fatigue cycle. A substrate made of UD S-glass/epoxy was used to demonstrate the concept of the sensor. S-glass/epoxy and YSH70/epoxy have different resin systems, but previous experience has proven that using the 913 curing cycle in an autoclave for co-curing them together results in a good bond between them. The properties of these materials are listed in Table 1. Additionally, Araldite 2015–1 by Huntsman, a two-component epoxy resin adhesive, which is extremely resistant to weathering and dynamic loading, was used to bond the sensor with the substrate.

Two different sensor lay-up configurations with different numbers of carbon layers were designed to assess the fatigue sensor concept: a) Sensor #1 with 3 plies and b) Sensor #2 with 5 carbon plies. Both carbon layers are made out of UD YSH70/epoxy with a central cut. Carbon sensors are covered by UD S-glass/epoxy layers on the bottom and top surfaces, as schematically shown in Fig. 9. The nominal substrate specimen dimensions are 500/400/20/2.5 mm overall length/ free length/ width/ thickness, respectively. The sensor's nominal dimensions are 320/10 mm total length/ width, respectively.

The risk of separating the sensor from the substrate has been minimized by introducing gradual ply drops rather than terminating the layers suddenly, i.e., the surrounding glass layers and the sensing carbon layers all have ply terminations at different locations. The energy release rate is proportional to the thickness of the discontinuous layer. By gradually dropping the plies, the change of discontinuous ply is always kept equal to one layer, and the energy release rate is minimized. This approach entails the top carbon ply having the shortest length, and the length increases downward incrementally to the bottom layer, which has the greatest length. Ply drops reduce the interlaminar shear stress concentration and stop any delamination propagation from the sensor ends, so delamination is expected to only initiate and propagate from the central cut. It is worth noting that the ply-drops are not included in finite element (FE) simulations as they do not significantly affect the results in the center of the sensor. Besides, the purpose of FE modeling is to acquire G_{II} values at the crack tip, rather than to simulate the propagation process.

4.2. Specimen manufacturing

Substrate and sensors were manufactured separately using the standard process for prepreg composites. First, the prepreg was cut and

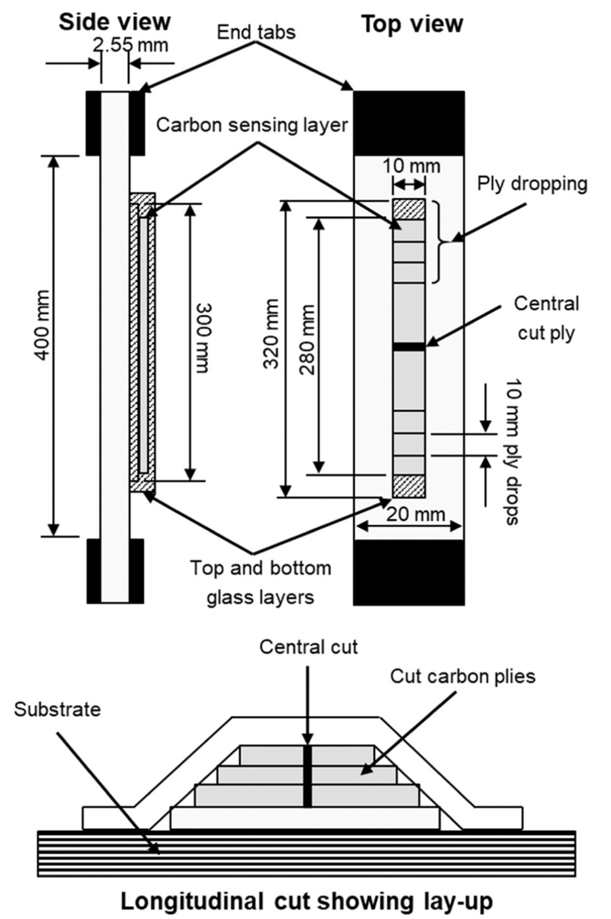

Fig. 9. Schematic of the lay-up and dimensions of manufactured specimens.

stacked up manually to fabricate uncured plates of 500 mm length and 100 mm width for the substrate and 320 mm length and 100 mm width for the sensor. To introduce the cut consistently in all sensing carbon layers, they are first stacked up and then the cut is introduced in all the layers in one go. A technique used in previous works by the team for introducing cuts with good precision [36] was used to ease the handling of the cut carbon layers and avoid the separation of the two cut uncured laminates. In this method, the carbon layers are not fully cut, and uncut areas are kept within the layer to keep the carbon layer as a single layer. Subsequently, a central incision was introduced by cutting through all the carbon layers before the glass layers were added to either side of the carbon layers. Finally, the hybrid sandwich laminate of glass/carbon layers was cured together in an autoclave. The standard bagging method on a flat aluminum tool plate was utilized to cure the plates in the autoclave. The prepregs specimen plates were cured for 90 minutes at 125°C and 7 bar pressure, a cycle recommended by Hexcel in the 913 epoxy resin data sheet and compatible with the other material.

The cured plates were cut using a diamond cutting wheel to the desired dimensions of the specimens and sensors mentioned in Section 3.1. Then, the 110 mm length of each end of the sensors was bonded to the substrate specimens using Araldite 2015/1 epoxy adhesive systems. To apply the adhesive, both surfaces were initially cleaned with a degreasing agent to eliminate surface contamination. Subsequently, a layer of resin/hardener mixture was applied to the dry joint surfaces, followed by fixing both the substrate and sensor using a mechanical clamp. The adhesive was allowed to cure at the ambient temperature for 24 hours to achieve maximum strength. It is worth mentioning that the substrate does not need to be flat and can have a curved shape, such as a cylinder. As long as both the cured sensor and substrate have the same initial curvature or shape, they can be bonded together, and the sensor's functionality should not be affected by the curvature. Finally, 1 mm thick aluminum end tabs were bonded to the specimens using the same adhesive system. Grips were used for 24 hours while the adhesive was cured to maintain the position and pressure on the bonded surfaces. Fig. 10 shows the manufactured tabbed substrate with attached hybrid sensors.

4.3. Test procedure

Uniaxial load-controlled tension-tension fatigue tests were conducted on the substrates bonded to 3- and 5-ply carbon layers sensors. A universal hydraulic test machine equipped with the Instron 8801 computer controller and a load capacity of 100 kN with wedge-type hydraulic grips was used. A sinusoidal load about the mean at a frequency of 5 Hz, a maximum load of 6.8 kN, and a stress ratio of 0.1 is applied to the specimens. The stress ratio is a quantitative measure of the variability of cyclic loading, expressed as the ratio of the minimum stress to the maximum stress. At every 500 cycles, a picture was taken to evaluate the damage growth by a digital camera, and the crack length was measured using ImageJ software. Fig. 11 shows the testing setup.

5. Results and discussion

5.1. Delamination propagation during fatigue loading

As described in the previous section, the crack extension in the hybrid glass/carbon sensor is monitored throughout the fatigue loading of the samples. It is noteworthy that the sensor remained securely bonded to the substrate throughout the entire test. Fig. 12 shows the visible crack extension at the interlaminar region of the top glass/carbon interface in the hybrid sensor with a 5-ply carbon layer at different fatigue cycles. This visual evidence serves to validate the concept of visualizing fatigue loading via delamination in the sensor. It is evident that monitoring and tracking fatigue-induced damage through interlaminar crack extension is a highly effective approach, and the sensor successfully captures this data. This not only provides valuable insight into the number of fatigue cycles but also offers a foundation for further analysis and improvements in sensor technology. The interlaminar crack extends gradually as fatigue loading continues and can be easily seen on the hybrid sensor. The crack growth is slightly faster at the edges due to edge effects, which agrees with the FE results shown in Fig. 7 for 0° fiber orientation in the glass layer.

Fig. 13 shows the results of experimental crack evolution during fatigue loading for two different sensor designs based on the number of middle carbon layers. As expected, in line with the simulation findings for two laminates, the rate of crack propagation is significantly greater in the laminates with a 5-ply carbon layer when compared to the laminate with a 3-ply carbon layer. Consequently, this leads to a greater crack length in the laminates with a 5-ply carbon layer after the same number of fatigue cycles. Furthermore, the experimental data implies a linear correlation between crack length and the number of cycles when represented on a logarithmic scale. This correlation offers valuable design parameter that can be harnessed for optimizing the sensor in different applications.

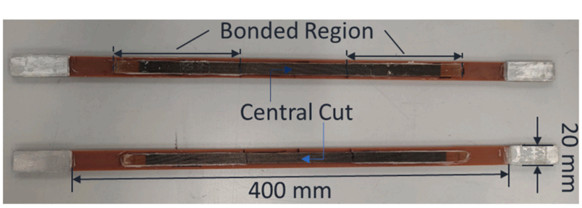

Fig. 10. Manufactured sensors attached to S-Glass/Epoxy substrate.

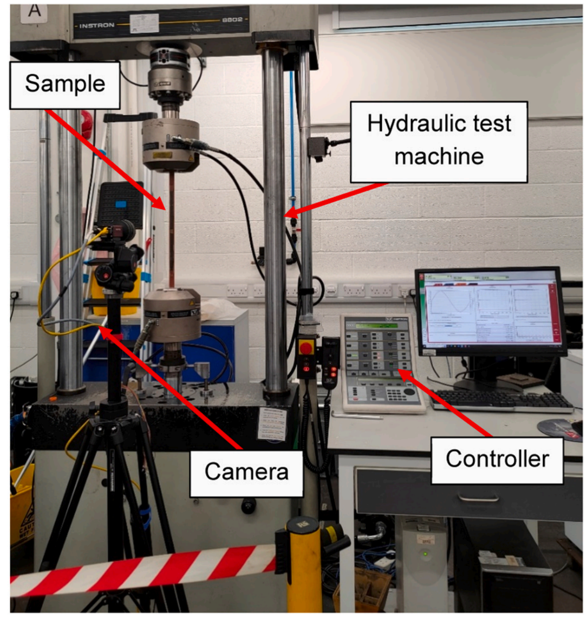

Fig. 11. Experimental setup.

5.2. Paris law for crack extension

The modeling methods used to anticipate fatigue crack propagation can be categorized into two main groups: models rooted in linear elastic fracture mechanics and models developed using cyclic cohesive zone modeling. Within the first group, models like the celebrated Paris law are employed to forecast the fatigue crack growth rate (da/dN), whereas, within the latter group, the concept of continuum damage mechanics is utilized to predict the fatigue damage growth rate (dD/dN) [37]. Within the linear elastic fracture mechanics framework, prevailing models for analyzing fatigue crack growth establish a connection between the crack growth rate and either the strain energy release rate or the stress intensity factor. Owing to their simplicity, energy-based models are frequently favored in the realm of composite materials [38]. In this paper, the Paris law is utilized to relate the rate of delamination growth to the change in strain energy release rate. The rate of crack propagation and delamination growth during fatigue loading can be described using the Paris law:

$$\frac{da}{dN} = C(\Delta G)^n \tag{1}$$

where da/dN is the rate of crack propagation and ΔG is the change in strain energy release rate in each cycle. Parameters C and n are material constants calculated empirically. In this section, the Paris law parameters are initially derived based on the experimental results obtained from the 3-ply carbon layer design for the sensor. Subsequently, using the obtained parameters, the Paris law is applied to a different sensor configuration with a 5-ply carbon layer design to predict the rate of crack propagation. Fig. 14 shows the crack propagation rate of the 3-ply carbon layer obtained experimentally as a function of ΔG calculated using FE results. Using a power curve fitting, parameters C and n are obtained as 624 and 6.84 respectively.

Now using the Paris law parameters obtained from curve fitting as shown in Fig. 14, the rate of crack propagation is predicted for a 5-ply carbon layer configuration. The results are shown in Fig. 15 compared to the experimental results. The results show good agreement with the experiments, indicating that the crack propagation rate can be predicted. Through FE analysis, one can determine the strain energy release rate at various crack lengths. By utilizing the acquired Paris law parameters, it becomes feasible to forecast the crack propagation rate as the number of fatigue cycles escalates and anticipate the number of

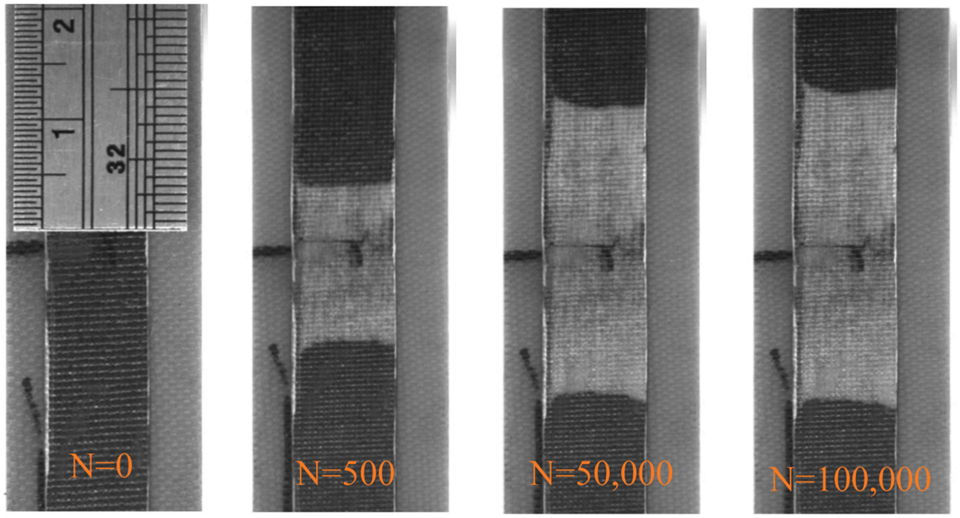

Fig. 12. Crack Growth results obtained from experiments before applying fatigue load and after 500, 50,000, and 100,000 cycles.

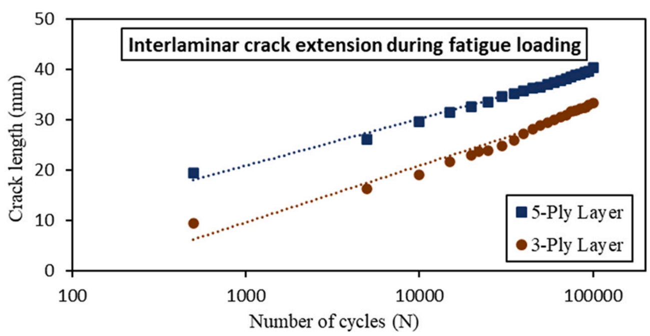

Fig. 13. Crack extension at different fatigue cycles for two sensor designs.

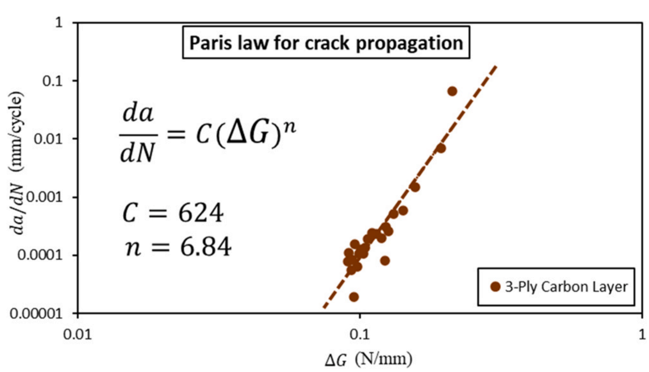

Fig. 14. Paris law parameters for a 3-ply carbon layer sensor.

cycles required to attain a specific crack length. Thus, the sensor configuration can be optimized based on the desired crack propagation rate. The applicability of the Paris law to the sensor can be useful for further development and refinement of this sensor technology. It shows the potential for a major advance in assessing and monitoring composite materials in diverse applications.

5.3. Challenges and future research works

The primary objective of this paper is to propose a new concept of utilizing hybrid composites as fatigue cycle counters; therefore, a limited number of tests are conducted in this initial phase. Nevertheless, it is imperative to expand the experimental scope by conducting a more extensive series of tests to ensure the reliability of the sensor and provide comprehensive data regarding the repeatability of the experimental results.

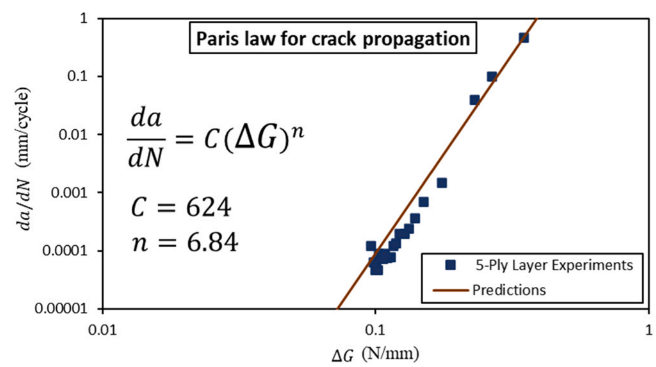

Fig. 15. Paris law prediction for a 5-ply carbon layer fatigue sensor.

The most important limitation of the current design is the fact that structures in real life are exposed to variable amplitude fatigue loads, and this sensor has only been studied for constant amplitude fatigue loads. In its current form, the sensor operates as a cycle counter under constant amplitude fatigue load independent from the substrate. The concept of this non-electronic sensor holds the potential for assessing substrate damage, but this entails integrating progressive damage models for both the substrate and the attached sensor, establishing correlations between delamination propagation in the sensor and substrate damage evolution. Advancing the sensor as an SHM technique requires extensive investigation, beginning with assessments under constant amplitude loads. Subsequent phases of research could broaden its applicability to variable amplitude loads and different load ratios, presenting challenging scenarios demanding comprehensive exploration and validation.

The aging process of the epoxy between the glass and carbon may lead to a change mechanical behavior and delamination growth rate, potentially deviating from the original design. Long-term adhesive functionality under diverse ambient conditions and severe weathering requires thorough examination to avoid debonding of the sensors over time. The current paper focused on flat sensor configuration. While the authors believe the sensor should behave consistently if it is curved, further experimental work is required to validate these assumptions.

6. Conclusions

A novel concept for a non-electronic fatigue sensor is proposed and tested to visualize fatigue cycles. The sensing mechanism relies on the gradual delamination of the glass/carbon interface under fatigue loading, visible to the naked eye. The delamination at the interfaces of glass/carbon hybrid composites is utilized for visualizing fatigue cycles. Finite Element Analysis (FEA) was used to assess the impact of design parameters on sensor function. Factors like bond length, fiber orientation in glass layers, and carbon layer thickness were numerically studied. Partial attachment of sensors was found to give symmetric delamination propagation in the top and bottom interfaces of the sensing carbon layer.

Two sensors with different carbon layer thicknesses were manufactured and explored under fatigue testing. Delamination propagation during fatigue loading was visually tracked, and Paris law parameters were established. The rate of crack propagation was predicted based on these parameters and compared to experimental results, demonstrating good agreement.

The promising results of this research present the potential for a non-electronic sensor for structural health monitoring and fatigue assessment in composite materials, offering a practical and visually accessible approach for tracking the fatigue load cycles. This sensor combines lightweight and thin characteristics with affordability, non-electronic operation, user-friendly readability, and eliminating the need for specialized operator training. Consequently, further development and refinement of this sensor technology could have significant implications for enhancing the safety and reliability of composite structures in various applications.

CRediT authorship contribution statement

Meisam Jalalvand: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Ali Mahmoudi:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Conceptualization. **Jose Acosta Correa:** Validation, Methodology, Investigation. **Michael Khonsari:** Writing – review & editing, Supervision, Project administration. **Mohammad Fotouchi:** Methodology, Investigation. **Michael Winsom:** Writing – review & editing, Supervision, Methodology.

Declaration of Competing Interest

The authors have no conflict of interest to report.

Data availability

Data will be made available on request.

Acknowledgements

Part of this work was funded under the UK Engineering and Physical Sciences Research Council (EPSRC) Programme Grant EP/I02946X/1 on High Performance Ductile Composite Technology in collaboration with Imperial College, London. The authors thank Hexcel for providing the glass layers. The data necessary to support the conclusions is included in the paper. J. David Acosta thanks Minciencias-Colombia for the provided funding through "Doctorados en el exterior No. 885" and School of Engineering, University of Southampton for the provided PhD scholarship. A.M. and M.M.K. wish to gratefully acknoweledge partial support for composite materials research from the US National Science Foundation, Grant number 2243755.

References

[1] A. Mahmoudi, M.M. Khonsari, Entropic characterization of fatigue in composite materials. Encyclopedia of Materials: Plastics and Polymers, Elsevier, 2022, pp. 147–162, vol. 2.
[2] T. Allen, S. Ahmed, P. Reed, I. Sinclair, S. Spearing, Underst. Seq. Damage Complex Hybrid. Compos. Met. Struct. Subj. Out. –Plane Load. Invest. Using Comput. Tomogr. (2015).
[3] S. Sanchez-Saez, E. Barbero, R. Zaera, C. Navarro, Compression after impact of thin composite laminates, Compos. Sci. Technol. vol. 65 (13) (2005) 1911–1919.
[4] S. Hassani, U. Dackermann, A systematic review of advanced sensor technologies for non-destructive testing and structural health monitoring, Sensors 23 (4) (2023) 2204.
[5] M. Mićić, L. Brajović, L. Lazarević, Z. Popović, Inspection of RCF rail defects–Review of NDT methods, Mech. Syst. Signal Process. 182 (2023) 109568.
[6] I.S. Ramírez, F.P.G. Márquez, M. Papaelias, Review on additive manufacturing and non-destructive testing, J. Manuf. Syst. 66 (2023) 260–286.
[7] R. Zinno, S.S. Haghshenas, G. Guido, A. VItale, Artificial intelligence and structural health monitoring of bridges: a review of the state-of-the-art, IEEE Access 10 (2022) 88058–88078.
[8] N.G. Panwar, S. Singh, A. Garg, A.K. Gupta, L. Gao, Recent advancements in battery management system for Li-ion batteries of electric vehicles: future role of digital twin, cyber-physical systems, battery swapping technology, and nondestructive testing, Energy Technol. 9 (8) (2021) 2000984.
[9] M.S. Malik, Model assisted POD of laser-ultrasonics NDT for train axles: a review. Proceedings of the 2016 International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT), IEEE, 2016, pp. 4645–4648.
[10] H. Towsyfyan, A. Biguri, R. Boardman, T. Blumensath, Successes and challenges in non-destructive testing of aircraft composite structures, Chin. J. Aeronaut. 33 (3) (2020) 771–791.
[11] S.S. Khedmatgozar Dolati, N. Caluk, A. Mehrabi, S.S. Khedmatgozar Dolati, Non-destructive testing applications for steel bridges, Appl. Sci. 11 (20) (2021) 9757.
[12] A. Wooldridge, Recent advances in automated ultrasonic inspection of Magnox power stations, Mater. Test. 49 (6) (2007) 290–298.
[13] M. Gupta, M.A. Khan, R. Butola, R.M. Singari, Advances in applications of Non-Destructive Testing (NDT): a review, Adv. Mater. Process. Technol. 8 (2) (2022) 2286–2307.
[14] Q. Ma, et al., Pipeline in-line inspection method, instrumentation and data management, Sensors 21 (11) (2021) 3862.
[15] W. Staszewski, G. Tomlinson, C. Boller, G. Tomlinson, Health Monitoring of Aerospace Structures, Wiley Online Library, 2004.
[16] K. Torabi, M. Shariati-Nia, M. Heidari-Rarani, Moving support technique for delaminatoin detection in laminated composite beams using the first natural frequency, J. Reinf. Plast. Compos. 36 (15) (2017) 1116–1128.
[17] F.-G. Yuan, Structural Health Monitoring (SHM) in Aerospace Structures, Woodhead Publishing, 2016.
[18] K.B. Katnam, L. Da Silva, T. Young, Bonded repair of composite aircraft structures: a review of scientific challenges and opportunities, Prog. Aerosp. Sci. 61 (2013) 26–42.
[19] V. Giurgiutiu, Structural health monitoring of aerospace composites, 2015.
[20] C. Kralovec, M. Schagerl, Review of structural health monitoring methods regarding a multi-sensor approach for damage assessment of metal and composite structures, Sensors 20 (3) (2020) 826.
[21] T. Dong, N.H. Kim, Reviews of structural health monitoring technologies in airplane fuselage maintenance perspective, 2018 AIAA/AHS Adapt. Struct. Conf. (2018).
[22] T. Ozkul, H. Kaplan, M. Dolen, ed. Wireless enabled fatigue sensor for structural health monitoring, Google Patents, 2014.
[23] P.D. OKULOV, Micro electro-mechanical strain displacement sensor and system for monitoring health and usage of a structure, ed: Google Patents, 2023.
[24] O. David-West, D.- Amafabia, G. Haritos, D. Montalvao, A review of structural health monitoring techniques as applied to composite structures, Struct. Durab. Health Monit. (2017).
[25] S. Rana, R. Fangueiro, A.G. Correia, A review on smart self-sensing composite materials for civil engineering applications, AIMS Mater. Sci. 3 (2) (2016).
[26] A. Todoroki, M. Tanaka, Y. Shimamura, Electrical resistance change method for monitoring delaminations of CFRP laminates: effect of spacing between electrodes, Compos. Sci. Technol. 65 (1) (2005) 37–46.
[27] A. Todoroki, K. Omagari, Y. Shimamura, H. Kobayashi, Matrix crack detection of CFRP using electrical resistance change with integrated surface probes, Compos. Sci. Technol. 66 (11-12) (2006) 1539–1545.
[28] P. Pissis, et al., Strain and damage sensing in polymer composites and nanocomposites with conducting fillers, Procedia Eng. 114 (2015) 590–597.
[29] G. Czél, M.R. Wisnom, Demonstration of pseudo-ductility in high performance glass/epoxy composites by hybridisation with thin-ply carbon prepreg, Compos. Part A: Appl. Sci. Manuf. 52 (2013) 23–30.
[30] C. Bakis, A. Nanni, J. Terosky, S. Koehler, Self-monitoring, pseudo-ductile, hybrid FRP reinforcement rods for concrete applications, Compos. Sci. Technol. 61 (6) (2001) 815–823.
[31] F. Nanni, G. Ruscito, G. Forte, G. Gusmano, Design, manufacture and testing of self-sensing carbon fibre–glass fibre reinforced polymer rods, Smart Mater. Struct. 16 (6) (2007) 2368.
[32] T. Rev, M. Jalalvand, J. Fuller, M.R. Wisnom, G. Czél, A simple and robust approach for visual overload indication-UD thin-ply hybrid composite sensors, Compos. Part A: Appl. Sci. Manuf. 121 (2019) 376–385.

[33] P. Suwarta, Pseudo-ductility of unidirectional thin-ply hybrid composites, Univ. Bristol (2020).
[34] P. Suwarta, M. Fotouhi, G. Czél, M. Longana, M.R. Wisnom, Fatigue behaviour of pseudo-ductile unidirectional thin-ply carbon/epoxy-glass/epoxy hybrid composites, Compos. Struct. 224 (2019) 110996.
[35] E.F. Rybicki, M.F. Kanninen, A finite element calculation of stress intensity factors by a modified crack closure integral, Eng. Fract. Mech. 9 (4) (1977) 931–938.
[36] G. Czél, M. Jalalvand, M.R. Wisnom, Demonstration of pseudo-ductility in unidirectional hybrid composites made of discontinuous carbon/epoxy and continuous glass/epoxy plies, Compos. Part A: Appl. Sci. Manuf. 72 (2015) 75–84.
[37] F. Teimouri, M. Heidari-Rarani, F.H. Aboutalebi, S. Karimi, L. Lessard, Experimental characterization and cyclic cohesive zone modeling of mode I delamination growth in glass/epoxy composite laminates under high cycle fatigue, Eng. Fract. Mech. 296 (2024) 109853.
[38] F. Teimouri, M. Heidari-Rarani, F.H. Aboutalebi, Finite element modeling of mode I fatigue delamination growth in composites under large-scale fiber bridging, Compos. Struct. 263 (2021) 113716.

Ali Mahmoudi: Dr. Mahmoudi is a Postdoctoral Researcher at Louisiana State University (LSU), where he is conducting research on fatigue and fracture of advanced materials with particular focus on remaining life assessment of composite materials. He has published over 15 peer-reviewed papers and a book chapter and secured 3 NSF-funded grants for research in the field of fatigue failure.

J. David Acosta: He is a PhD Candidate in the field of Composite Materials at the Department of Mechanical Engineering at University of Southampton (UoS). His research areas are the mechanical behavior of hybrid composites and sensor application of hybrid and standard composites in various industries from aerospace applications to renewable energy solutions.

Meisam Jalalvand: Dr. Jalalvand is a Lecturer in Composite Materials and Structures at the University of Southampton (UoS). He is an expert in failure analysis and FE modeling of composites. His research has provided new explanations and significantly improved understanding of the failure process of hybrid composites. He has published over 100 journal papers in the field of composites.

Mohammad Fotouhi: Dr. Fotuhi is an Assistant Professor in Structural Health Monitoring at Delft University of Technology. He is an expert in development of SHM techniques for engineering structures, lightweight/smart bio-inspired structures, 4D printed self-morphing structures and multi-functional materials. He has published over 120 articles in these research fields.

Michael R. Wisnom: Dr. Wisnom is a Professor of Aerospace Structures at the University of Bristol and Founding Director of Bristol Composites Institute. He is a leading expert on the mechanics and failure of fiber reinforced composites, with over 400 published papers. He is a Fellow of the Royal Academy of Engineering and a member of the steering board of the UK National Composites Center, Editor in Chief and European Editor for Applied Science and Manufacturing of the international journal Composites Part A.

Michael M. Khonsari: Dr. Khonsari holds the Dow Chemical Endowed Chair and is Professor of Mechanical Engineering at Louisiana State University. He is the Director of NSF Center for Innovations in Structural Integrity Assurance (CISIA). CISIA is a university-industry-government cooperative center. He has published over 400 journal papers in the fields of tribology and fatigue. He is the Field Chief Editor of Frontiers in Mechanical Engineering.