Structural Health Monitoring of Carbon Fiber Composite Lamination Using Electrical Resistance

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Abstract. It focuses on a composite material made of glass and carbon fibers in this paper. The composite can be actively monitored and controlled by the self-sensing of the carbon fibers. However, due to the high stiffness and brittleness of the composite material, damage often occurs instantaneously. It is difficult to monitor damage patterns and control damage through factors such as fiber type variables and displacement relationships. This is why monitoring the health of composite fibers is an important direction, which has major implications for the aerospace, industrial and automotive sectors. In this project, the main focus is to monitor the electrical conductivity of carbon fibers online by breaking thin layers and observing the changes in their conductivity, and to understand changes in condition through changes in current. In addition, the composite design of this project can be applied to the monitoring of large planar materials, as well as to applications in important areas such as aerospace. In making further comparisons, it can be seen that the 5 mm thin layer of carbon fiber is more sensitive in the process of self-sensing, while the change in resistance is more noticeable when damage is received in the period.

Keywords: Structural Health Monitoring · Carbon Fiber Composite Lamination · Electrical Resistance · Three-point bending test

1 Introduction

There are more and more high-tech products made of composite materials, such as aerospace or automotive, and even the latest batteries. They are becoming increasingly popular due to their outstanding properties, such as their high strength, low weight and fatigue resistance, Composites are combinations of two or more materials with different physical behavior and chemical states. In particular in this test, the materials used are fiber reinforced polymers. As the properties of composites are usually more variable, engineers consider their design structure and components to minimize failure during the design of composites [1].

V. C. M. Leung et al. (Eds.): Qshine 2023, LNICST 573, pp. 61–71, 2024.
https://doi.org/10.1007/978-3-031-65126-7_6

In fields such as aviation and construction, it is important to ensure safety margins, as sudden damage can potentially lead to injury or death as well as huge financial losses. In these important areas, sudden failures as well as small residual load capacities are not allowed. This is why higher safety margins and more conservative structural designs are the dominant design approach in current designs, while another problem with engineered materials is that they break down without prior detectable damage and warning [2].

2 Literature Review

The composite material is made by two or more components. Composite material can be made by using fiber that are cured within a resin. Using a combination of different materials, taking advantage of their strengths and reducing the impact of their weaknesses is an important idea in designing composite materials. The most common types are combining carbon fibers and glass fibers with a thermosetting resin to create either a CFRPs or GFRPs. The use of multiple fiber-reinforced polymer laminations to form a new composite material with enhanced mechanical properties, such as compressive and tensile resistance, and the consideration of how to efficiently monitor the new composite material, based on previous research by scientists, has become an important key, and finally some of the advantages and disadvantages of previous monitoring methods in relation to the composite material in this experiment are presented.

3 Aims and Objective

How to monitor the health of composite materials is an important current research issue. It can effectively contribute to the development of several areas where composites are used, such as aerospace engineering and the automotive industry. However, in the traditional composite fiber industry the damage itself is unpredictable and sudden as it can be caused by different kind of stresses and pseudo-plastic deformations. There are many different methods of detection, but most of them do not reflect the changes in the material in real time and are also too expensive. This project therefore proposes a method to monitor changes in material resistance based on the fact that the resistance of thin carbon fibers changes gradually during damage. Research done by Meisam has shown that damage to fibers varies linearly (Rev, Jalalvand et al. 2019) and therefore the health of the material can be monitored by detecting changes in resistance based on this theory. The aim of this project is to design another sensor based on resistance variation, to experiment in order to check if the sensor is usable, and to design and test the sensor in order to achieve the best possible results, observing through experimentation and results whether it is sensitive and efficient.

Research Objective 1. Research test samples and target sensors based on existing literature and conjecture.

Research Objective 2. Analysis of the change in resistance of the sample and its force and displacement profiles.

Research Objective 3. Using a hybrid S-shape to detect damage on a flat plane and resistance changes monitored using a carbon glass hybrid.

4 Research Methodology

It describes the methods and techniques used in the selection of materials, the preparation process, and the design of the testing process for this project. In particular, first, it will be described in detail what materials are used to prepare the samples, as well as the preparation process and methods. Then, it will be described the test process of the experiment and other equipment used in the experimental process, last, it is going to be described the detail of the whole experiment and the theoretical data will be given, including the theoretical currents and the theoretical stresses generated by the experiment.

Material Selection

In addition, for sample preparation we used T700/XC130 unidirectional prepreg carbon fiber as the sample body and S -Glass/913 and M46JB unidirectional prepreg thin carbon fiber as the sensor. The base material was made from T700 carbon fiber manufactured by Toray of Japan. When selecting the substrate material, it was considered that the main carbon fibers are mainly T300 and T700, both of which contain a large amount of carbon, but the overall performance of T700 is significantly better than that of T300. In the selection of the sensing layer, we chose to use a thin carbon fiber sandwiched between the two glass fibers. As the thin carbon fiber chosen, M46JB, has a similar tensile strength to T700, but obviously the compressive strength of M46JB is weaker than that of T700.T In this experiment, glass fibers were chosen to wrap the thin carbon fiber because, as seen in Meisam's model, there are three different damage modes for composites made from high and low strain materials, so in order for the sensing layer of carbon fibers to break before the glass fibers in the isolation layer, a thin layer of carbon fibers with a lower degree of strain than the glass fibers must be used as the induction material (Fig. 1). (Fotouhi, Jalalvand et al., 2017)

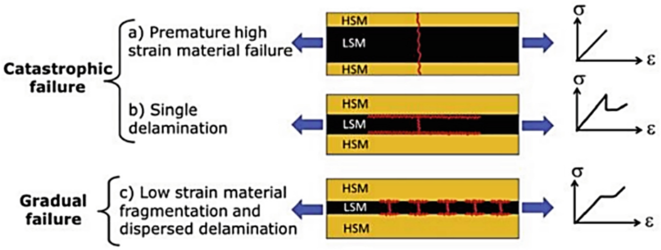

Fig. 1. Possible failure modes in a three layers UD hybrid made from HSM and LSM (red lines show fracture) (a) single crack through the whole specimen, (b) single crack in the LSM followed by instantaneous delamination, and (c) multiple fracture and localised stable pull-out of the LSM

Typically, the basic constituent material of a carbon fiber reinforced material is usually a combination of multiple or unidirectional fiber orientations, rearranged to provide different mechanical properties. A single unidirectional (UD) fiber arrangement, where all the fibers in the resin are aligned in one direction with no voids or breaks. Another type of arrangement is where the fibers are aligned at 0 and 90 degrees, this is known as multi -directional (MD) fibers (Fig. 2). This multi -axial material has better tensile and compressive resistance than uniaxial material, but because it is manufactured at an angle, it is less malleable.

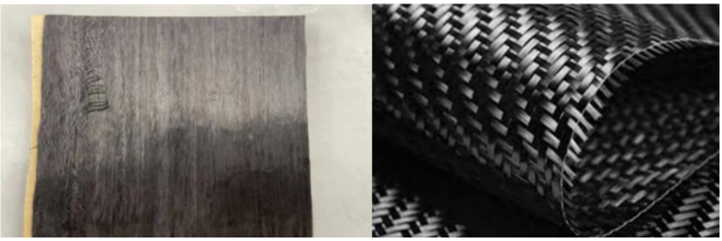

Fig. 2. UD carbon fiber(A), MD carbon fiber(B)

Experiment Test Group

The carbon fibers in the experimental group will be linked to each other, showing S-shaped connections, which then means that the data from the experimental group will affect each other. This control group can be used to see if the resistance will be affected by the occurrence of fiber breaks. Having established that the resistance will change due to fiber breakage, then this experimental group has the advantage that only two electrodes are needed to complete the experiment due to the large area it covers. The main reason for using two different widths of samples was to see the rate of change in resistance by comparing the two sizes of 5 mm and 10 mm. In the graph below, sample 1 is the control group of 10 mm, sample 2 is the control group of 5 mm, sample 3 is the experimental group of 5 mm and sample 4 is the experimental group of 10 mm, shown as Fig. 3.

Fig. 3. Kinds of simple.

Three-Point Bending Test

After the indentation test, the material is tested using the three-point bending method, which is one of the simplest and most effective methods of testing laminates and is widely used in destructive testing due to its simple construction and the fact that it does not require much manipulation. For this test, the sample is placed on a jig and a multimeter is connected to the two sections of copper to read the resistance data. The movement speed of 7 mm/min is entered into the control of the hydraulic press and the test is started (Fig. 4).

Fig. 4. Three -point bending test.

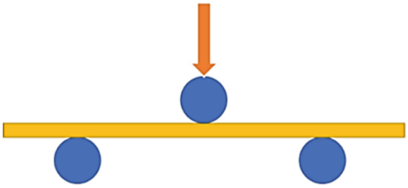

Fig. 5. Injury patterns under three-point bending

The three-point bending process is achieved mainly by applying pressure to the tip, during which the sample undergoes a process of gradual destruction. The following diagram shows the principle of three -point bending (Fig. 5).

During the three-point bending experiment, the sample started to break gradually when it was loaded to a high enough stress. As this sample was a mixed sample, the surface glass fiber started to break when it was loaded to 0.7 KN, the glass fiber broke completely when it was loaded to 1.2 KN, then the load was reduced to 0.6 KN and then the carbon fiber started to break gradually.

The images show that the entire damage process is produced gradually, and based on the experimental images it can be seen that the samples start with damage and end up with damage (Fig. 6).

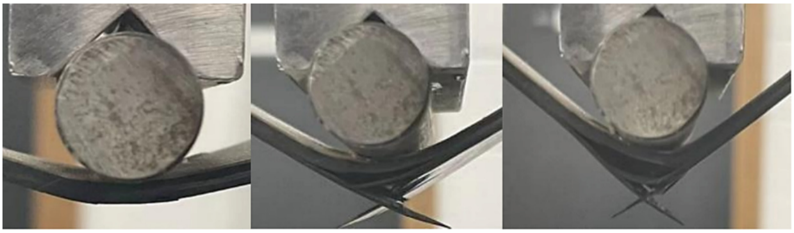

Fig. 6. The process of three-point bending test

Theory of Three-Point Bending Test

When bending deformation occurs in the three-point bending method, the fibers near the bottom elongate and those near the top shorten. According to the planar hypothesis, the fiber state changes gradually from stretching to compression along the height of the cross section from the bottom to the top, then there must be a layer in between where the length of the fiber remains constant, this layer is called the neutral layer (Fig. 7).

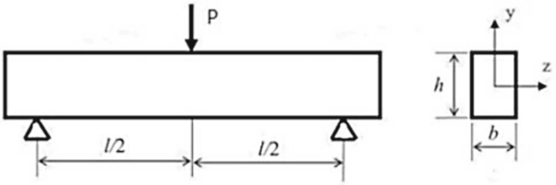

Fig. 7. Three-point bending method model

In the three-point bending test, when viewed from the front, it can simply be seen as a simply supported beam subjected to a concentrated pressure. Three-point bending should theoretically result in a linear distribution of positive stresses along the beam in the cross-sectional area when loaded.

$$\sigma = \frac{M}{I_z} y \tag{1}$$

where σ is the stress, M is the moment, Iz is the moment of inertia of the cross-section to the z-axis and y is the distance in the cross-section to the y-axis. The maximum positive stress at the danger point of the beam is:

$$\sigma_{Max} = \frac{M_{Max}}{I_z} y_{Max} \tag{2}$$

For rectangular section specimens:

$$M = \frac{P \times l}{4} \qquad I_z = \frac{bh^3}{12} \tag{3}$$

Substituting Eqs. (3) into (2) yields the new equation

$$\sigma_{bb} = \frac{3P \times l}{2bh^2} \tag{4}$$

where P is the load and L is the span, b is for width, h is for thickness.

In the case of a sample based on this equation, the maximum shear stress is calculated a

$$s\sigma_{bb} = \frac{3P \times l}{2bh^2} = \frac{3 \times 1.5\,KN \times 150\,mm}{2 \times 50\,mm \times 9\,mm^2} = 800\,Mpa \tag{5}$$

According to the Table 1, its standard value is 880 Mpa, However, as this design contains other fibers of different thicknesses or patterns, this data can only be used as a reference value for the main body of the sample, so in principle the maximum acceptable shear stress for this design should be lower than this value.

5 Results

This experiment focused on the fabrication process of the self-sensor, which was designed using an innovative mixture of carbon fiber and thin layers of E glass fiber, and investigated the advantages and differences between this combination and the use

Table 1. Mechanical properties of curing

Properties	Numerical value	Unit
Tg Onset(DMA)	**140**	°C
Tensile Strength	**645**	MPa
Compressive Strength	**515**	MPa
Flexural Strength	**882**	MPa
Flexural Modulus	**60.1**	GPa
Interlaminar Shear Strength	**69.8**	MPa
Tg Peak(DMA)	**148**	°C

of plain carbon fiber strips alone. As the fiber orientation was also considered in this carbon fiber experiment to affect the magnitude of the current, a unidirectional thin layer of carbon fiber was used in this case so that the consistency of the current could be maintained throughout.

In the three-point bending test, since the three -point bending test causes large shear stresses, data were collected from the start to sample failure and finally the changes in resistance and the reasons for these changes were analyzed in conjunction with the changes in the curves.

5 mm Bending Test

In this section the experimental data on the 5 mm three-point bending method is described. Unlike the above, as this design is a hybrid design, the standard T700 carbon fiber bending performance criteria above can only be used as a reference value, so according to the experimental process, the bending performance is significantly lower compared to T700, only around 800 Mpa, so it is speculated that it is possible that the mixture of glass fiber and thin-layered carbon fiber has affected the bending performance.

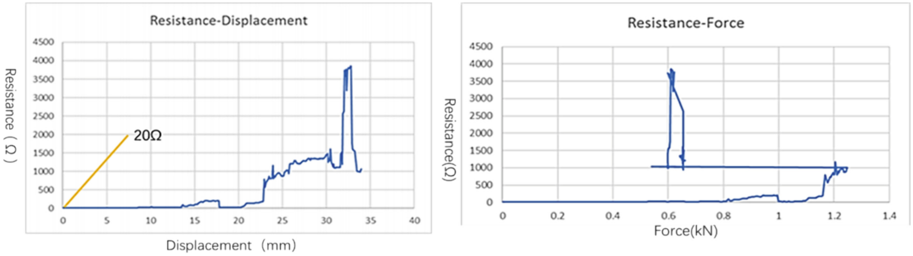

Fig. 8. 5 mm experimental group resistance displacement curve(top) and 5 mm experimental group resistance Force curve(bottom)

According to the data we can see that there is a relatively obvious increase in resistance after the indentation test, as can be seen from the graph, at 25 mm of the experiment is the maximum stress, when the carbon fiber begins to destroy, it can be concluded that

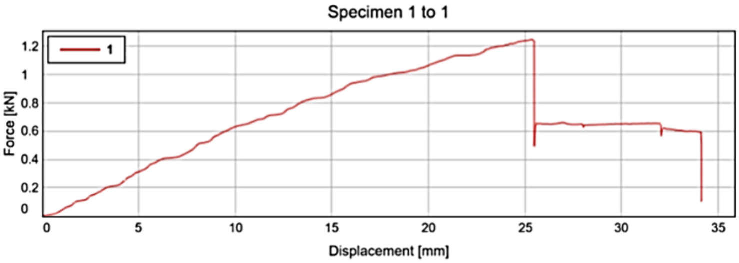

Fig. 9. 5 mm experimental group displacement and Force curve

in the 25–30 mm zone, the resistance begins to rise, indicating that the carbon fiber body is further destroyed in this zone, when in the 30–35 zone, the carbon fiber is completely destroyed and the resistance rises to 4000 Ω (Fig. 8). When the carbon fibers are completely destroyed, the loading force is removed and the fibers spring back, at this time some of the fibers reduce in resistance because the stress is reunited (Fig. 9).

10 mm Bending Test

The 10 mm three-point bending test is also primarily a comparison with 5 mm, observing the change in resistance of two different widths of carbon fiber to determine which is more appropriate.

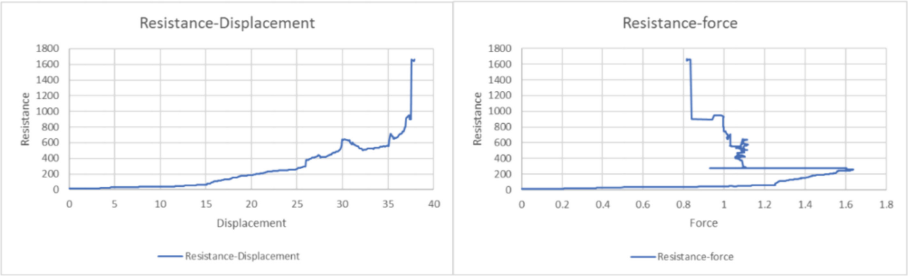

Fig. 10. 10 mm experimental group resistance displacement curve(left) and 10 mm experimental group resistance Force curve(right)

By comparing the two sets of plots, it can be found that the 5 mm images of resistance and Force are relatively similar to the 10 mm images on the three -point bending method, but on the resistance displacement curve, it is obvious that the rising trend of the 10 mm curve is smoother, so after the comparison, it is more recommended to use a 10 mm wide thin layerof carbon fiber as a self-sensor (Figs. 10 and 11).

Damage Mode Analysis

In this section, the damage pattern of the experimental product and the image in the above figure will be analyzed in detail, as the damage to the sample occurred gradually over the course of the test and this fiber hybridization slowed down the catastrophic rate and so led

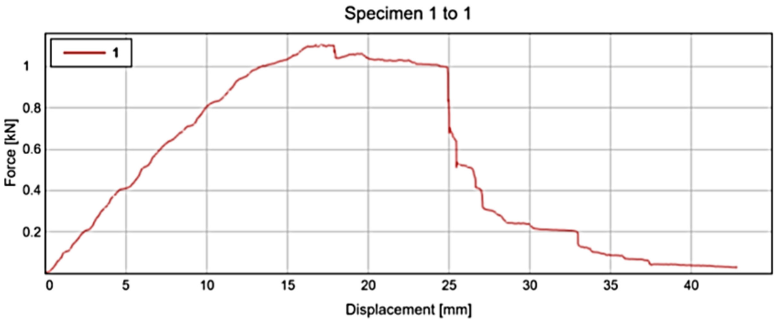

Fig. 11. 10 mm experimental group displacement and Force curve

to the phenomenon of pseudo-stretchability. Analysis of the sample damage showed that shear damage dominated at the upper end of the sample, while delamination dominated from the middle to the lower plies, shown as Fig. 12. However, the main change in resistance in this test was due to the fracture of the thin carbon fibers, which was mainly due to tensile stresses, while the delamination of the lower plies was mainly due to shear stresses, so the design of this test was reasonable.

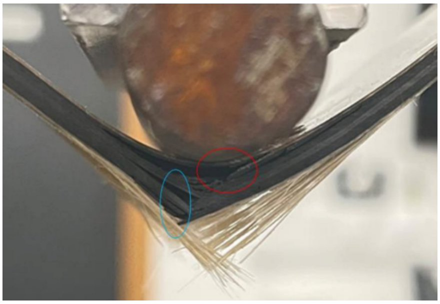

Fig. 12. Injury patterns under three -point bending

6 Conclusion

In this project, a hybrid thin-layer carbon/glass fiber self-sensing method is proposed. It is innovative in that it changes the traditional case of applying the carbon fibers directly to the object to be sensed. Also, by using an S -shape instead of the traditional direct strip, it allows for greater coverage and a larger area to be monitored than just partial detection, while its more holistic nature makes it more effective for monitoring a whole plane rather than monitoring a broken location, and also has a greater improvement in monitoring the effects of certain unseen damage. Regarding the experiment, this experiment uses the controlled variable method to create differences for different variables. By designing groups of different widths as well as different styles, several experiments were conducted to get the correct data and then compared to draw conclusions. Damage to the carbon/glass blend and fracture of the carbon fibers was observed by using Three Point Bending method. The pictures show that where pressure is applied the upper layers are damaged by shear stresses leading to kinking and the lower layers are damaged mainly in the form of delamination leading to failure.

In conclusion, this study has been designed, experimented and concluded that it is feasible to monitor the electrical conductivity of this hybrid carbon/glass fiber blend and that this composite fiber can also be seen as a self-sensor.

Acknowledgments. This project is supported by the funding of Guangdong Province Key Laboratory of Intelligent Detection in Complex Environment of Aerospace, Land and Sea. (2022KSYS016).

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