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RESEARCH ARTICLE

Effect of Embedded Strain Gage on the Mechanical Behavior of Composite Structures

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ABSTRACT

Fiber reinforced composites are increasingly used in several fields such as aeronautics and civil engineering due to their increased strength, durability, corrosion resistance, resistance to fatigue and damage tolerance characteristics. The embedding of sensor networks into such composite structures can be achieved. In the present study, glass fiber reinforced Epoxy composite with integrated strain gage was analysed. Firstly, the mechanical behaviour of this material with embedded strain gage is investigated. The as-prepared samples have been tested under tensile and flexural loading in order to study the effects of the strain gage embedding on the structural stiffness and strength of the composite. It was found that the tensile stiffness decreases by 5.8% and the tensile strength decrease by 1.5% when the strain gage embedded in the material. On the other hand, the flexural strength and stiffness is increased, respectively, by 1.5% and 5.5% with an embedded strain gage. The experiments showed that embedded strain gage is functional and demonstrated the successful integration of sensor networks into composite parts. The obtained results confirm that integrated strain gage can be used for the Structural Health Monitoring (SHM) of glass fiber reinforced Epoxy composite.

Keyword: Mechanical behaviour, Smart Composite, Structural Health Monitoring, Strain gage.

1 Introduction

Composites materials are increasingly used to improve the structural performance in a several advanced applications: aerospace, space vehicles, cars, boats, civilian infrastructure [1, 2]. Composite materials have high mechanical properties at a low weight [2, 3]. Besides, the methods to inspect and insure the reliability of composites materials are expensive. Composites materials damage is difficult to detect because the delamination and fiber breakage occurs inside of the material and the damage are not often apparent at the surface. To ensure the good functioning of composite structures, the non-destructive testing methods (NDT) are widely used [4, 5]. These methods include ultrasound, laser, acoustic emission, X-ray, Foucault currents, thermal wave imaging [5, 6]. Overall, the NDT methods are the most accurate approach for inspecting composite materials. However, they are expensive, and they take time and require that the component or structure must be removed from service for inspection. The developments of smart composite materials open new fields to improve the structural health monitoring and life cycle of structures [7-9]. Currently, the insert of smart parts by integrating sensor networks in the composite become possible. These networks record different physical signals [10, 11] and can even work as active components.

The good use of composite materials requires understanding of the mechanical responses and monitoring of the performance of each component in the composite under mechanical loads and external environmental. Several analytical and numerical solutions have been proposed for predicting the static and dynamic response of composite structures with integrated components. Rabinovitch et al. [12] analyzed the bending deformation in the smart sandwiches composites having the foam core and glass/face sheet composite with embedded piezoelectric materials. The analytical solution is obtained from the higher order deformation theory. Baillargeon et Vel [13] used the electro-mechanical shear coupling effect of PZT materials which have been integrated in a sandwich cantilever beam to suppress vibration. The sandwich beam is made from aluminum matrix and a core composed of two piezoelectric shear actuators and foam. Experimental tests have shown the effectiveness of shear actuators for active vibration suppression. Abot et al. [14] presented an overview of the carbon nanotubes sensor capacity to detect the delamination initialization and separation in layered composite materials. The low cost and simplicity of wire sensor opens a new integrated sensor technology to monitor the structural health in real-time. Ye et al. [15] introduce a system which is able to automatically and continuously monitor the structural performance of composite structures. Miscellaneous sensor network components are examined like thermocouples and metallic strain gauges [16-18] , optical fibers [19, 20], or flexible circuit boards and chip resistors [21, 22].

In the present study, strain gage is embedded into glass fiber reinforced Epoxy composite and the mechanical behaviour of the composite with and without embedded strain gage is investigated. The aim is to identify changes in the mechanical properties of the composite. In order to compare the mechanical properties of a conventional glass fiber/epoxy composite and the alternative structure with embedded strain gage [23], the tensile and three-point bending tests are used. The first part of this paper is devoted to a presentation of the experimental procedures. Results of systematic measurements of mechanical properties are gathered in second section.

2 Experimental Procedures

2.1 Specimen Preparation

The studied composite material is a glass fiber reinforced Epoxy composite. The role of the epoxy resin is to tie the fibers (cohesion role), and to ensure the transmission of stresses. The epoxy resin was mixed with its hardener at the manufacturing stage, before being impregnated into the dry reinforcement fabric to make the 'prepreg' reinforcement. The glass-epoxy prepreg was provided by Hexcel Company under the trade name of HexPly® M9.6G/37%/300H8/G, whereby M9.6G is the resin type; 37% is the resin content by weight; 300H8/G is the reinforcement reference and G represents E-Glass fiber. The matrix further ensures the strength of the material in the transverse direction to the reinforcement. The glass fiber reinforcement provides mechanical strength of the material (traction, compression, fatigue). Two types of specimens were prepared: reference specimens without embedded strain gage and smart specimens with embedded strain gage.

2.1.1 Reference Specimens

The composite material was prepared by contact molding. The aluminum mold surfaces are 500x 500 mm²; they are coated with an unmolding Cirex SI 041 WB as shown in Figure 1. The surface of the mold is thoroughly cleaned to be ready for the use, by removing any dust and dirt from it. 4 glass-epoxy prepreg sheets of dimension 30 x 300 mm² are pre-cut in a roll for each test tube to develop. The completed stacks are transferred into an evacuated molding press

(Figure 2). The consolidation process is executed with a constant pressure of 0.3 MPa and a temperature of 100 °C for 4 hours. The cooling is done at room temperature. The consolidated glass fiber /epoxy plates have a thickness of 1.2 mm. Then, specimens of 300 x 25 mm were cut.

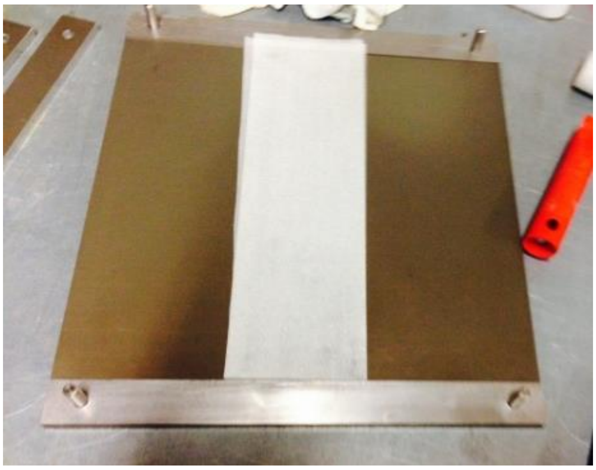

Figure 1 : *Mold used to prepare the specimens*

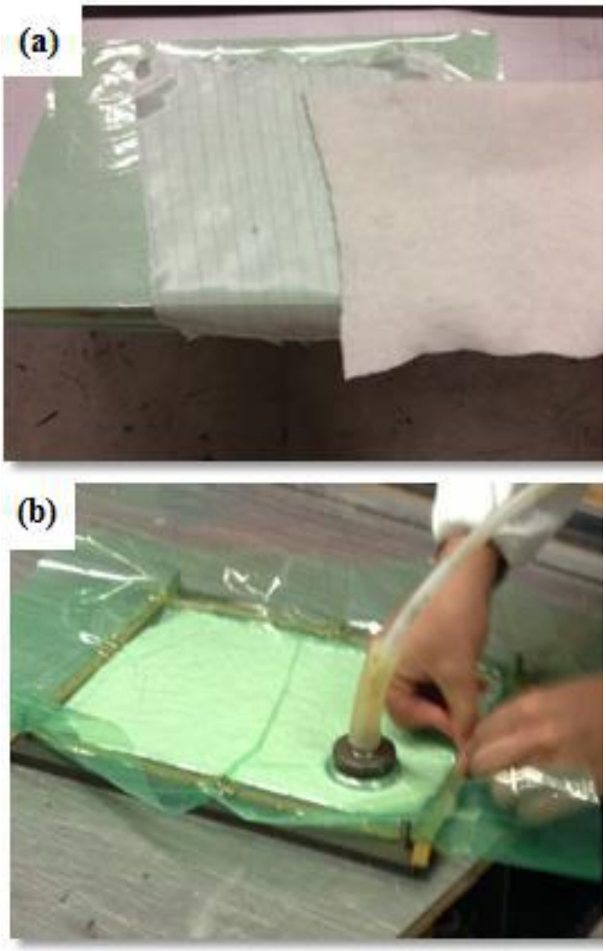

Figure 2 : *Specimens preparation (a) compacting materials (b) vacuum*

2.1.2 Smart Specimens

The samples with embedded strain gages are manufactured in a similar way and also consist of 4 glass-epoxy prepreg layers. Each specimen contains a strain gage that is positioned between the first and second layer (Figure 3). The strain gage is oriented in the longitudinal direction. To connect the strain gages to an external data logger, metallic wires are utilized. During the layup process, these wires are lead through the composite in transverse direction as shown in Figure 4. The role of these specimens is to confirm the good functioning of an embedded strain gage and observe the intrusiveness. The strain gage used is this study is 1-LK13E-3/350 produced by HBM.

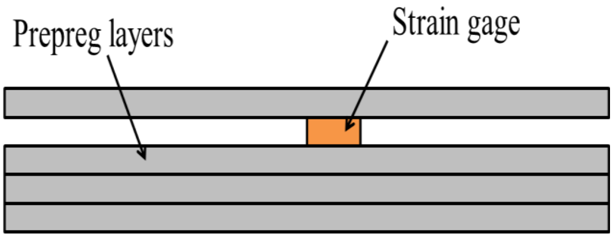

Figure 3: *Diagram of the specimen stack with strain gage*

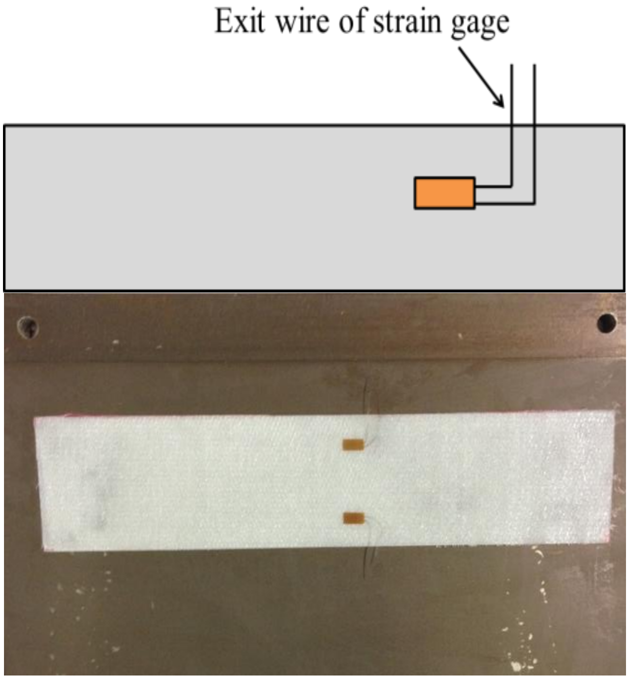

Figure 4: *Representation of the gage strain in the specimen*

2.2 Tensile Testing

The tensile tests were performed on an INSTRON 5569 machine at a fixed crosshead speed of 2 mm.min^{-1} until failure. A dumbbell-shaped specimen of rectangular cross section is used as shown in Figure 5. The Modulus is determined from the slope of the stress–strain curve for the specimen with embedded strain gage and without strain gage. 3 specimens for each configuration were tested.

Figure 5 : *Dumbbell-shaped specimen*

2.3 Three-point Bending Test

The flexural strength and modulus of glass fiber /Epoxy composites with embedded strain gage and without embedded strain gage were evaluated in a three-point bending test using a BOSE 3520 device equipped with a 100 kN load cell. Three specimens for each configuration were tested with a crosshead speed of 2 mm/min. During the test, the deflection of the specimen is measured directly beneath the punch by means of a contacting displacement measuring device. The specimens with embedded strain gages are connected to the Wheatstone bridge by additional copper wires in order to record the measured strains (Figure 6).

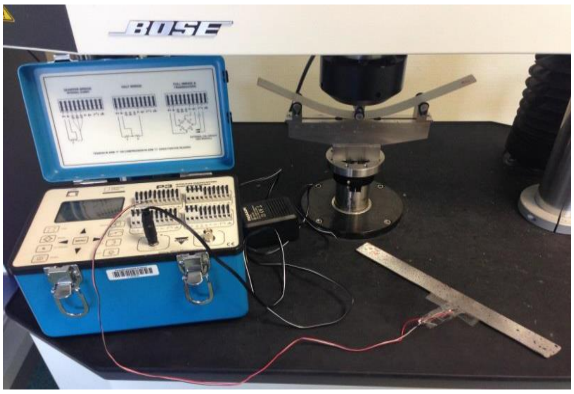

Figure 6 : *Connection embedded strain gages to the Wheatstone bridge*

These results are compared with data simultaneously recorded by the BOSE 3520 measuring device. The findings of these investigations are the basis to correctly interpret the signals of embedded strain gauges. All tests were performed at room temperature.

2.4 Fatigue Test

In this paper, the goal of three-point bending fatigue test is to analysis of fatigue behaviour of glass fiber/epoxy composite with embedded strain gage. The signal is sinusoidal with a frequency of 20 Hz (300000 cycles). The fatigue tests were performed with load level of 100 MPa. These tests allow to assess the loss of rigidity according to the imposed stress. Also, three-point bending fatigue tests were carried out on BOSE 3520 machine.

3 Results and Discussion

3.1 Tensile Testing

The insertion of a strain gage between two plies of glass-epoxy prepreg during manufacture is considered as default, which can initiate premature delamination [24, 25]. In the following, we will present our assessment of the impact of the embedded strain gage on the mechanical performance. The tensile test was performed on specimens of 4-ply without embedded strain gage (reference) and specimens including the strain gage (instrumented). Finally, to generate a statistical trend, three tests were performed in each case. Young's modulus is measured during tensile tests. It is estimated from the slope of the stress–strain curve. Figure 7 shows the normalised tensile strength and stiffness of glass fiber/epoxy specimens of reference specimens and instrumented specimens. The tensile stiffness decreases by 5.8% and the tensile strength decrease by 1.5% when the strain gage embedded in the material. Thus, insertion of strain gages in a glass –epoxy change a little it's rigidity. It is also noted that these tests were conducted with a thin specimen (4 ply only). Under such conditions the thickness of the sensor (45±10 µm) is not negligible and its intrusiveness will be much more pronounced than in the case of the use of thicker specimens.

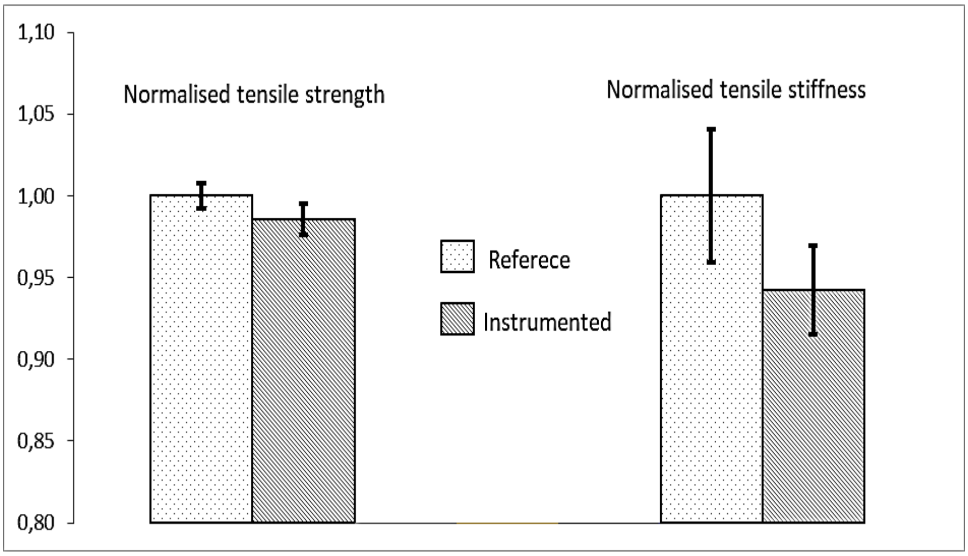

Figure 7 : *Normalised tensile strength and stiffness of glass fiber/epoxy specimens*

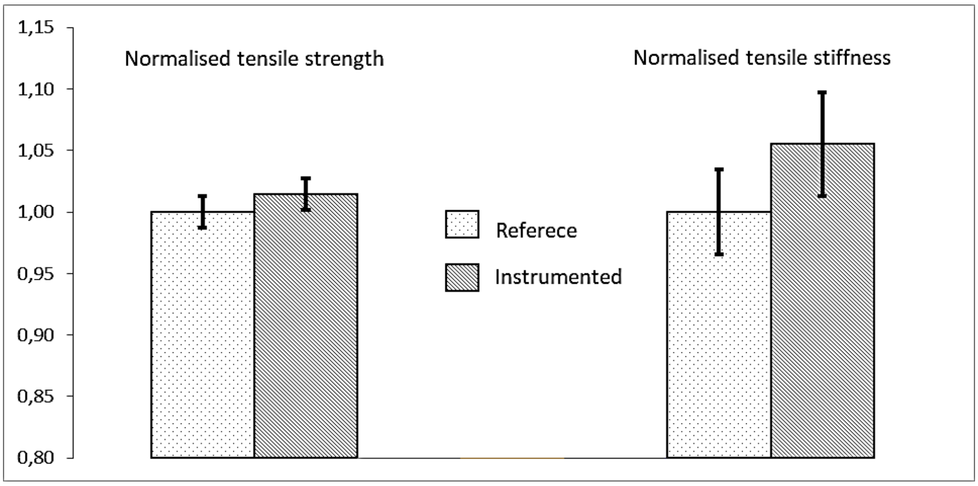

Figure 8 : *Normalised flexural strength and stiffness of glass fiber/ epoxy specimens*

3.2 Three-point Bending Test

Also, the three-point bending test was performed on two types of specimens: reference and instrumented. Figure 8 gives an overview of the results obtained in the flexural tests. It appears that the flexural strength and stiffness is increased, respectively, by 1.5% and 5.5% with an embedded strain gage. The flexural strength is greater in the presence of the buried detection system. This is explained simply by considering that insertion of a strain gage increases significantly the thickness of specimen (1.32 mm). These differences will be obviously reduced, even undetectable on thicker specimens. The results of the flexural tests are in good accordance with results found in the literature for other materials, which show no serious reduction of the flexural properties of fibre-reinforced composites by embedded sensor network components [7, 21].

3.3 Three-point Bending Fatigue Test

Figure 9 shows two cycles taken at different times of the three-point bending fatigue test with embedded strain gage: cycle at the start and cycle at the end of the test. There is no significant difference between these cycles. Delamination or sign of weakness on the specimen instrumented was not observed after the fatigue test. It would thus seem that the insertion of a strain gage in glass fiber / Epoxy composite does not cause of delamination. However, the fatigue test was realized only on 30000 cycles, which corresponds to an initiation phase according to the theories of fatigue. On the other hand, loading/unloading cycles indicate significant stress–strain hysteresis. The interior area generated by these curves represents the dissipated energy during cycling.

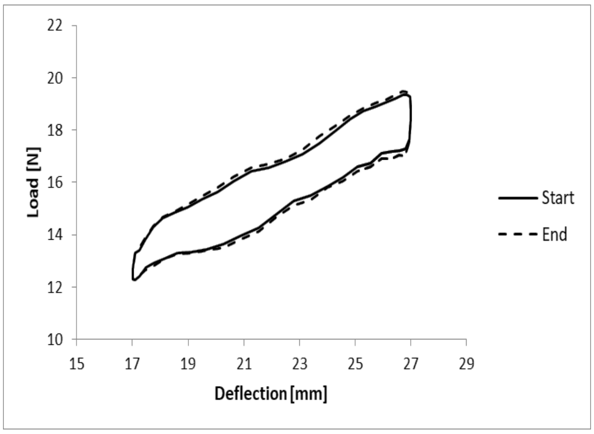

Figure 9 : *Hysteresis curves in bending for glass fiber / epoxy composite with embedded strain gage*

3.4 Strain Measurement by Embedded Strain Gages

In addition to the mechanical properties, it is also essential to check the strain gage behaviour throughout the life cycle of a specimen. Thus, the deformation obtained by strain gage is compared with the deformation of the specimen measured by the INSTRON 5569 device, as shown in Figure 10. The diagram includes stress-strain curves obtained for a chosen specimen. Strain gages measure smaller strains than INSTRON 5569 device for a given stress state. Under the assumption that the strain gages are bonded to the surrounding composite structure only by the matrix, the low shear modulus of epoxy is likely to be the reason for this behaviour. Strains of the composite are only partially transferred to the stiff metallic strain gauge. Therefore, the monitoring of composite structures with embedded strain gauges has to be used carefully and an initial calibration of the composite-integrated sensor network may be helpful.

4 Conclusions

This study focuses on the insertion of strain gauges in a composite structure and their ability to control the mechanical behaviour of fiber reinforced Epoxy composite. The performance of composite-integrated strain gages is evaluated. The mechanical tests (tensile, three-point bending and fatigue) showed that the embedding of strain gages into fiber reinforced Epoxy composite slightly alters the mechanical behaviour of the structure. Moreover, all of these tests were performed on specimens with a small thickness (1.2 mm) comparable to the sensors thickness and thus the impact on thicker structures should be almost imperceptible. In addition, the results show significant differences in strains measured by integrated strain gages and Instron device (tensile testing machine). Therefore, an initial calibration of embedded strain sensors is necessary. Subsequently, it is possible to monitor the strain state of the composite structure.

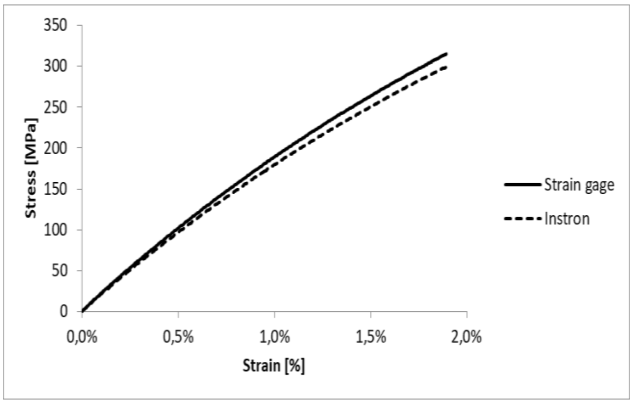

Figure 10 : *Glass fiber/Epoxy specimen under tensile load: stress-strain curves measured with integrated strain gages and Instron (tensile testing machine)*

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