Structural Health Monitoring System of Composite Beams with Surface Bonded and Embedded Fibre Bragg Grating Sensors

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Abstract. Fibre Bragg Grating (FBG) sensors have been frequently used for Structural Health Monitoring (SHM) of aerospace structures due to their advantages. One of the most important advantages is that FBG sensors can be embedded into composites. In this paper, manufacturing methods of composite specimens with surface mounted and embedded FBG sensors for simple bending tests are given. After manufacturing, it was observed that all sensors were intact and ready for bending tests. Procedure for bending tests is also explained including loads applied, boundary conditions, test setup and the peripheral equipment. Results of bending tests show that the system is an appropriate one for SHM purposes.

Introduction

Structural Health Monitoring (SHM) is a discipline of detecting and interpreting of adverse changes in a structure in order to improve reliability and reduce life cycle costs [1]. SHM is also defined in the literature as continuous monitoring of the state of the structures with embedded or mounted sensors with minimum human intervention to observe structural integrity [2].

Being an alternative to Non-Destructive Testing (NDT), SHM with embedded FBG sensors provides in-situ (online) monitoring opportunity [3]. This opportunity gives several advantages. Expensive routine maintenances, which cause aircraft out of service and require heavy labor force, are not needed anymore [4]. Furthermore, it is possible to reduce loss of time of manual detection and repair of damages through correct localization of damage. It is also possible to prevent damages through early detection. With data obtained from online monitoring, life of the monitored structure can be estimated and with simple precautions, life of the structure can be maximized [4]. Because of those, SHM systems with embedded FBG sensors are expected to play a key role in keeping structural integrity of composite structures, monitoring of structure life and detection of possible damages.

FBG sensors are increasingly being used for SHM and damage detection applications due to their advantages over other sensors such as durability, stability, chemical and physical compatibility, ability to measure very high strain values, high sensitivity, light weightiness, ability to withstand harsh environment and immunity to electromagnetic interference [5-9]. Also, more than one sensor could be placed on one fibre optic cable [5,10,11]. Yet, the most important advantage of FBG sensors is the possibility of embedment into the composite structures. Since they are small and have lightweight, embedment into the laminate is conducted without affecting the strength of the host structure [12].

Manufacturing of Composite Beams with Embedded and Surface Mounted FBG Sensors

Three identical composite beam specimens were manufactured by using prepregs. One of the beams, named as "1st Specimen", was manufactured without any sensor. However, one FBG sensor was mounted on the surface and one conventional strain gage was mounted on the opposite surface. Other beams, 2nd and 3rd specimens, were manufactured with one FBG sensor embedded between certain layers; unidirectional (UD) and woven respectively. After manufacturing, single FBG sensor was mounted on the surfaces of each specimen. All the sensors are located at the centre of ply planes, but have different thickness coordinates. Therefore, thickness position comparison is then made in this study. The sensors have orientation along axial direction since the axial strains will be measured during bending test.

Pedrazziani et.al. [13], and Kunzler and Udd [14], successfully conducted SHM and damage detection with embedded FBG sensors. In some studies, precautions such as teflon tube placement around the fibre optic cable at ingress and egress regions of structure were taken to prevent damage of the cables from the stress concentrations occurring [13,15,16].

Manufacturing the beams from one plate is not suitable considering the health of the fibre optic cables. Removing the beams with embedded sensors by cutting them from one plate is a very difficult task. Therefore, the prepreg materials were cut in planned dimension and laid accordingly. However, in width direction, the layers were cut longer than planned such that the free edges of the beam were to be smoothened with a cutting operation using a band saw.

Measurements were obtained carefully before the embedding process to correctly place the part that includes the FBG sensor on fibre optic cables. The wavelengths of the sensors were observed before embedment procedure to ensure the health of the sensors.

To protect the cables from the stress concentrations at ingress-egress regions, teflon tubes are used. The layer on which fibre optic cables with teflon tubes are placed can be seen in Fig. 1. Fibre optic cables are hard to observe since they are very thin, but they are mounted on the middle of the beam in axial direction and they are evacuated with covering teflon tubes. Following this, the remaining prepreg materials were laid such that laminates with embedded sensors are completed.

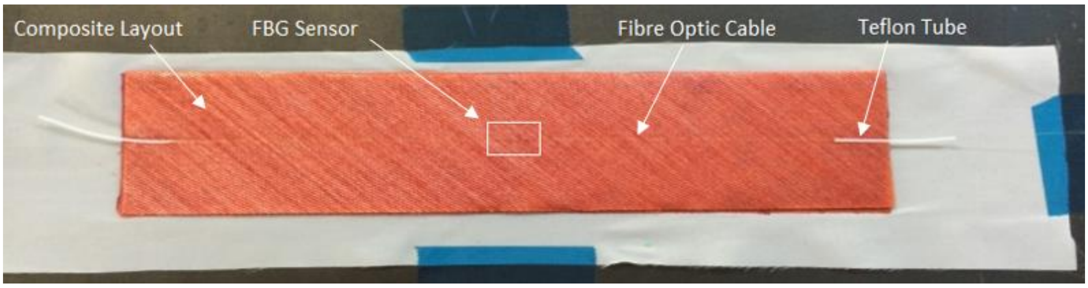

Fig.1. The layer on which fibre optic cable with teflon tubes are placed

Health of embedded sensors were checked again by observing their wavelength data. Pigtail connectors of FBG wire were cut before curing since they could melt because of high temperatures. After cure of the beams, the connectors were re-joined to the wires using fusion splicer device. Splicer connects two separate fibre optic cables by means of a laser light.

Having completed the manufacturing of the composite beams with embedded FBG sensors, other FBG sensors and strain gage were mounted on the face of the beams. One of the composite beams with embedded and surface mounted FBG sensors are shown in Fig. 2. The beam with surface mounted FBG and strain gage is also presented in Fig. 3.

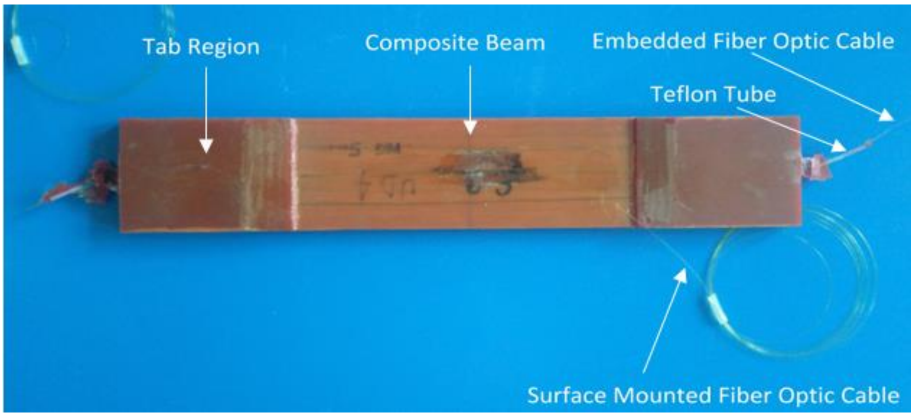

Fig. 2. Beam with Embedded and Surface Mounted FBG Sensors

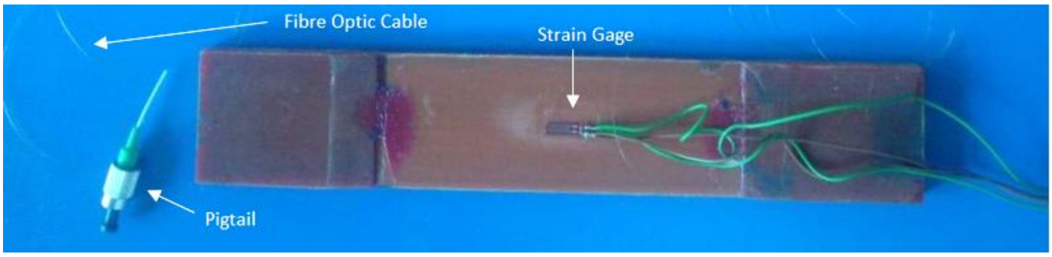

Fig. 3. Beam with Surface Mounted FBG Sensors and Strain Gage

Test Procedure

Simple bending tests were applied to specimens to observe data quality of FBG sensors. Comparison is made in two ways. First one is that the data recorded from FBG sensor are compared to that of calibrated strain gauge. Those sensors were bonded to opposite faces of the specimen. Therefore, opposite strains of the same magnitude is expected. After verification of FBG calibration, FBG's with the same calibration were used to observe other specimens including surface bonded and embedded sensors. Second method is to compare all data to strain results of 3-D Finite Element Analyses (FEA).

In Fig. 4, test setup of one of the specimens is shown where the specimen was fixed at one of the tab region through a clamp. Mass of 2.1 kg was hinged to supply a static load. Load position was a point on the surface of the free tab region. That point was in the middle width-wise of the specimen to avoid an additional torque effect. Axial load position was the same for all specimens and is taken consistent with Finite Element Model (FEM). Sensors were connected to its interrogator systems through wires.

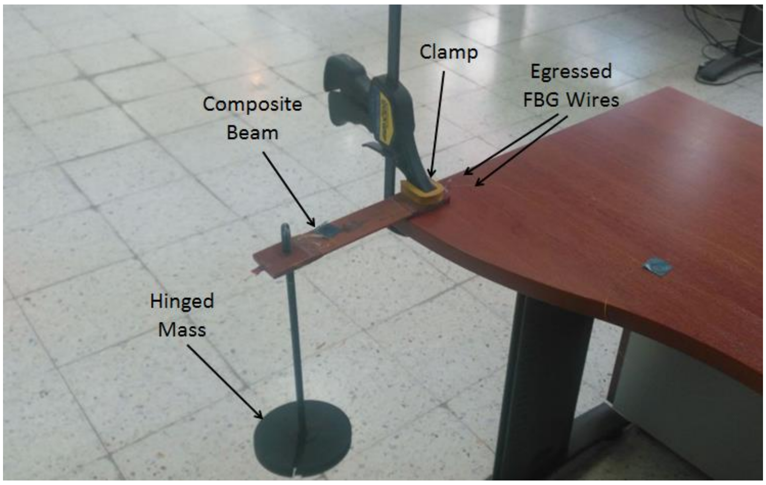

Fig. 4. Test Setup of Composite Specimens with Embedded and Surface Mounted FBG Sensors

Unloaded strain value of the sensors were adjusted as zero by resetting and then, lumped masses were added successively. Steady state strains of the sensors were taken as final strain values. Although the system became completely static, there was some fluctuation on the recorded data due to background noise. This noise was simply eliminated by taking mean value of strain data recorded after the mass was hinged.

Results

All results under fixed load is provided in Table 1. Sensors located on opposite faces are expected to give negative strain value with the same magnitude. To eliminate sign confusion, absolute value of strains and thickness-wise locations from neutral axis is taken. Since the structures are symmetric in thickness direction, neutral axis is expected at the middle axis through the thickness direction, when one dimensional beam (1-D) approach is made. Furthermore, according to 1-D beam theory, strain distribution along thickness direction can be assumed to be linear as given in Eq. 1.

$$\varepsilon = \kappa z. \tag{1}$$

where κ is constant curvature along thickness direction (z).

Table 1. Absolute Value of Strain [με] Measured by FBG Sensors and of FEA Result

Specimen	Absolute Value of Strain (|ε|) [με]		
	Woven - |z|=0 mm	UD - |z|=1.29 mm	Surface - |z|=2.21 mm
1st Specimen	-	-	407.0 373.8*
2nd Specimen	-	255.5	496.7
3rd Specimen	9.2	-	504.9
Theoretical - FEA	0	189.7	308.1

*Strain gauge used instead of FBG Sensor

As seen from results of 1st Specimen in Table 1, FBG sensor on the face has approximately the same strain magnitude with that of calibrated strain gauge on the opposite face. Therefore, FBG sensors are proven to have close accuracy.

Result obtained from the 2nd Specimen in Table 1 shows that the strain values at the same axial location is proportional with thickness-wise location from neutral axis as given in Eq 1. Proportionality constant κ can be found to be 2.21×10^{-4} mm^{-1} and 2.25×10^{-4} mm^{-1} for the sensors at |z|=1.29mm and |z|=2.21mm respectively. Very close curvature values show that strain is linearly proportional with z values, which is expected because of 1-D beam theory. Moreover, 3rd specimen has a sensor on its neutral axis. The strain result of that sensor is close to 0, which is also consistent with Eq. 1. However, some strain still exists, which may be because of very small offset from neutral axis caused by manufacturing imperfections.

All sensors at the surfaces (i.e. the last column of Table 1) give different strain magnitudes. It means that different specimens have slightly different mechanical parameters, which also shows the manufacturing of the specimens comprises some imperfections.

On the other hand, the FEA results show that theoretical model is not consistent with real specimens. Therefore, model updating is required including some reduction on the mechanical parameters such as Young's and/or shear modulus.

Conclusion

Manufacturing of composite specimens with embedded and surface mounted FBG sensors and their Structural Health Monitoring (SHM) application have been shown in this study. Successfully manufactured specimens underwent a simple bending test. With successful manufacturing methods, appropriate SHM system was created.

Manufacturing of specimens with embedded FBG sensors require additional key points. Manufacturing experience shown in the study, protective tubes were successfully added to prevent failure at ingress-egress regions. Pigtail connectors were cut out and spliced back after cure to prevent melting of connectors during the curing process. Bending force was applied to specimens through a weight addition and FBG sensors provided healthy and accurate results. FBG measurement is consistent with that calibrated strain gauge. Likewise, FBG strain results in different layers are also consistent with 1-D beam linear strain theory. FBG at neutral axis gives strain value close to zero. However, FEA results are not consistent with measurement ones and therefore, a model update is required as the material properties were not taken/assumed accurately enough.

In the future studies, different load conditions can be applied such as static tension, torsion, tension/torsion and dynamic modal tests. It is also possible to embed multi-mode sensors and thus to check spatial consistency in measurements.

Acknowledgement

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