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TORSION TEST OF COMPOSITE BEAMS USING FIBER BRAGG GRATING SENSORS FOR STRUCTURAL HEALTH MONITORING APPLICATIONS

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ABSTRACT

Fiber Bragg Grating sensors are commonly being used for Structural Health Monitoring of aeronautical structures. Fiber Bragg Grating sensors are convenient especially for Structural Health Monitoring of composite structures, such as helicopter blades and wind turbine blades, considering the ability of embedment between the layers. In this study, a Structural Health Monitoring system of composite beams equipped with surface bonded and embedded Fiber Bragg Grating sensors is introduced. Torsion tests of the composite beams are conducted to observe the performance of the system by monitoring the torque and shear strain. Validation of the test results are achieved by comparing the results obtained from the Finite Element Analyses and the performed tests. In addition, manufacturing methods and precautions to avoid plausible harms to the sensors are presented.

INTRODUCTION

Structural Health Monitoring (SHM) is the process of constantly monitoring the features which are indicators of the health of the structure. SHM is advantageous considering increased safety by detecting damages before failure and reduced maintenance costs by decreasing the number and extent of routine maintenance [Garcia et al., 2015]. Aeronautical structures subjected to harsh environmental conditions, such as helicopter blades and wind turbine blades or large composite aircraft components with limited access after assembled to the aircraft are possible candidates for SHM [Pedrazzani et al., 2012; Kahandawa et al., 2012].

Fiber Brag Grating (FBG) sensors are preferred for SHM of composite structures considering their high sensitivity, lightweight, and immunity to electromagnetic interference, but especially for the ability to be embedded into the layers of a laminate [Ramly et al., 2012].

FBG sensors might be used to measure strain which is considered as a feature indicating the health condition of the structure. Pedrazzani et al., successfully detected the defects during the fatigue testing of a wind turbine blade by monitoring the strain with distributed FBG sensors [Pedrazzani et al., 2012]. Murayama et al. used multiplexed FBG sensors to monitor strain of a wing structure [Murayama et al., 2010]. They obtained strain distribution around the stress

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concentration regions of interest such as bonded joints. Lee, et al. used embedded FBG sensors to measure dynamic strain of a subscale wing under real-time wind tunnel testing [Lee et al., 2003].

In this particular reseach study, composite beams instrumented with embedded and surface bonded FBG sensors are subjected to torsion. Shear strain and torque results from the tests and from the Finite Element Analyses (FEA) are compared. Accurately and efficiently measuring the shear strain is the first step through FBG sensors for damage identification applications as a future work.

METHOD

Manufacturing of the Composite Beams Equipped with Surface Bonded and Embedded FBG Sensors

Two composite beams are manufactured from prepreg layers with the same layup. Layup consists of unidirectional composite layers, woven composite layers and isotropic adhesive film layers with the stacking sequence as;

$$[0_8/Film/(\mp 45)_{Woven}/(\mp 45)_{Woven}/Film/0_8].$$

The first beam (namely S1T) includes two surface mounted FBG sensors which are bonded to the structure after the curing process. The second beam (namely S2T), on the other hand, comprises two embedded sensors and one surface bonded FBG sensor. Embedded sensors are implemented to the structure during the layup process. One of the sensors is placed between the unidirectional layers and the other is placed between the woven layers.

Teflon tubes are used around the fiber optic cables as a precaution against the stress concentrations at the egress points. In Figure 1, a fiber optic cable with Teflon tube during the embedment process is presented. Fiber optic cable is placed such that FBG sensor is in the middle of both the length and the width of the beam, where the maximum in-plane shear strain is expected.

All the sensors are placed in position of 45° degree from the axial direction in order to be more sensitive to the shear strain. Remaining part of the sensors that will be used to connect to the interrogator system are evacuated from a region at the long sides of the beams which are in between the grips of the test machine. FBG Interrogator System and connection parts could also be seen in Figure 2.

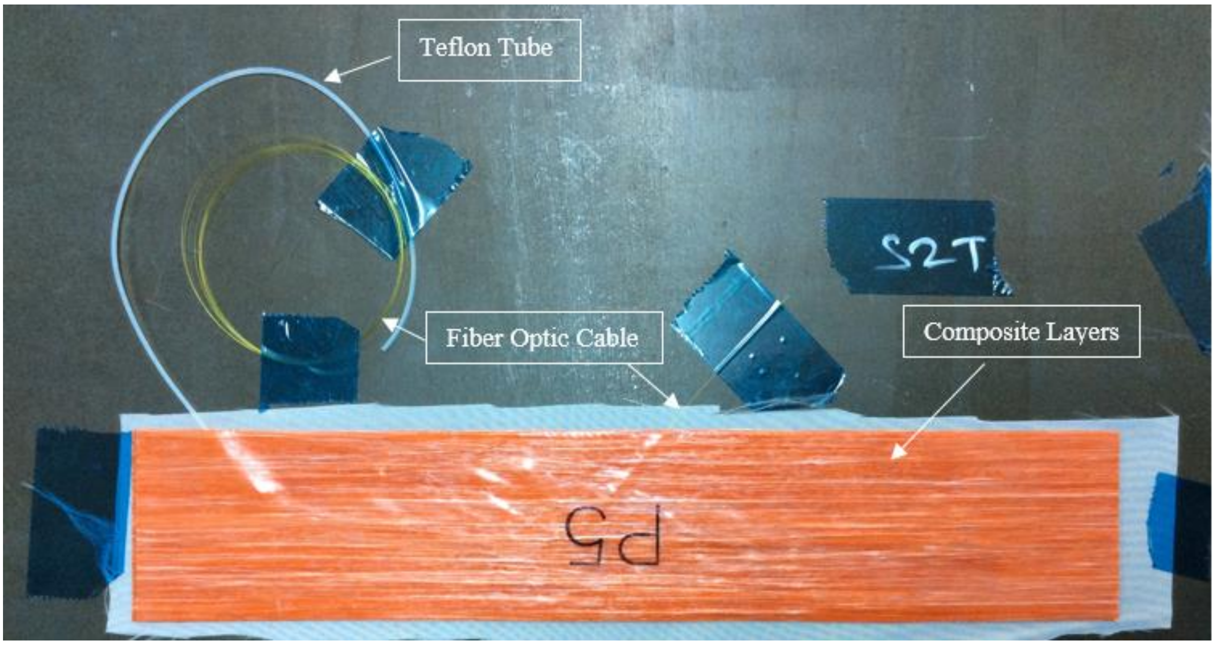


Figure 1: FBG Sensor with Teflon Tubes during Embedment Process

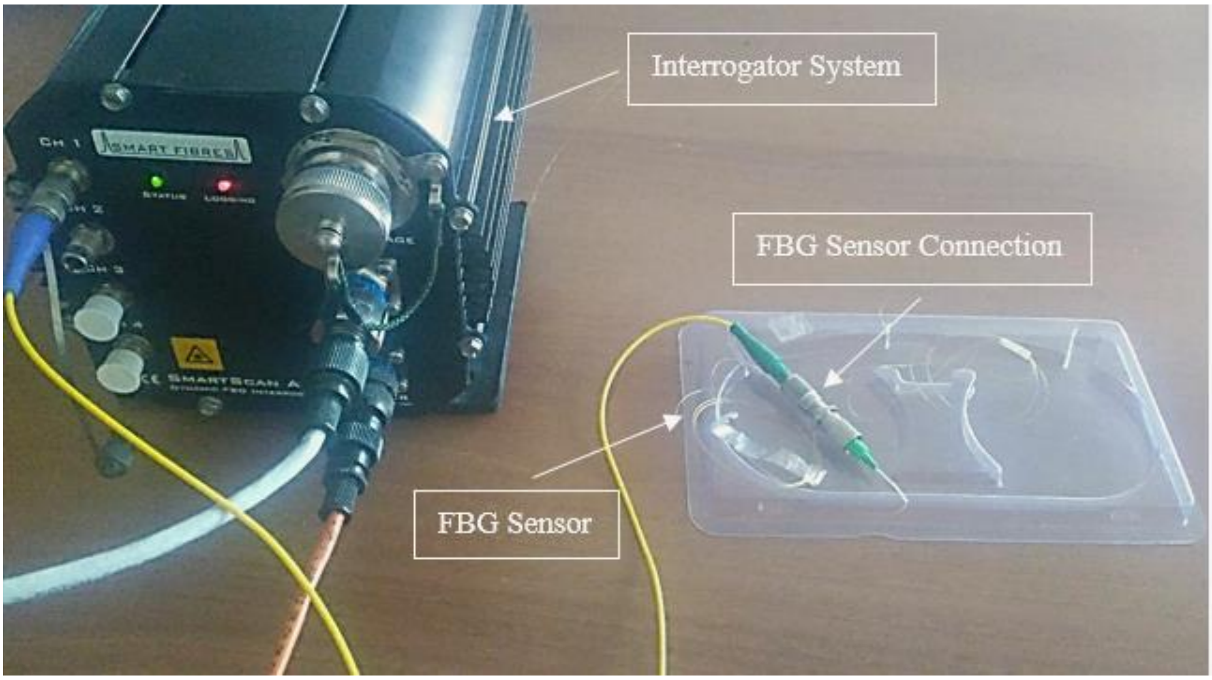


Figure 2: Interrogator System Connected to the FBG Sensor

Torsion Test of the Composite Beams

Torsion test of the composite beams, S1T and S2T, are performed using MTS 809 tension-torsion test system. The beams are twisted for a 20° of twisting angle under rotation control. Axial load is kept at zero by allowing the movement in longitudinal direction. Tests are conducted three times to observe the repeatability. In Figure 3, S2T which is twisted to the maximum angle of twist is presented. Bottom end of the structure is twisted while the upper end is held still. During the tests, the torque and the angle of twist values are recorded from the load cell of the machine, on the other hand, strain is measured by using FBG sensors.


Figure 3: S2T under 20° Angle of Twist

Finite Element Analysis for Torsion of the Composite Beams

Finite Element Model (FEM) for the torsion test is implemented such that it simulates the test as close as possible. Boundary conditions are applied to the structure using reference points coupled to the surfaces in contact with the grip of the test machine, as seen in Figure 4. One end of the beam is constrained in all displacement and rotation degrees of freedom while the other end is restrained in all degrees of freedom except the displacement and rotation along and around the x axis respectively in order to apply the angle of twist.

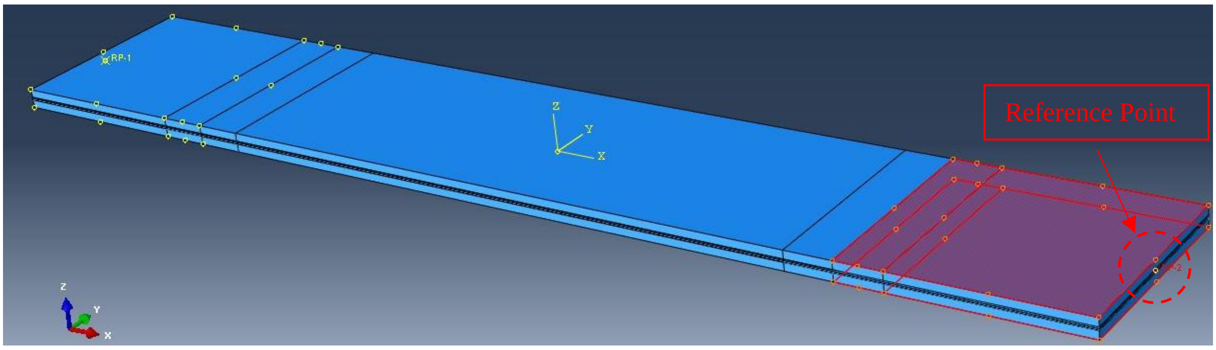


Figure 4: Reference Point Coupled to the Surfaces in Contact

Composite beams are modeled with 3D SOLID C3D8R finite elements which are 8-node linear brick elements using the commercial finite element code ABAQUS® and then linear elastic properties of the materials are input to the FEM. Mesh convergence study is conducted and a mesh structure which results in accurate and rather fast solution is implemented as seen in Figure 5. Also, the analysis are performed by considering the nonlinear effects of the geometry. The mesh structure consists of 12 elements in thickness direction with a total of 135000 finite elements which is seen in Figure 6.

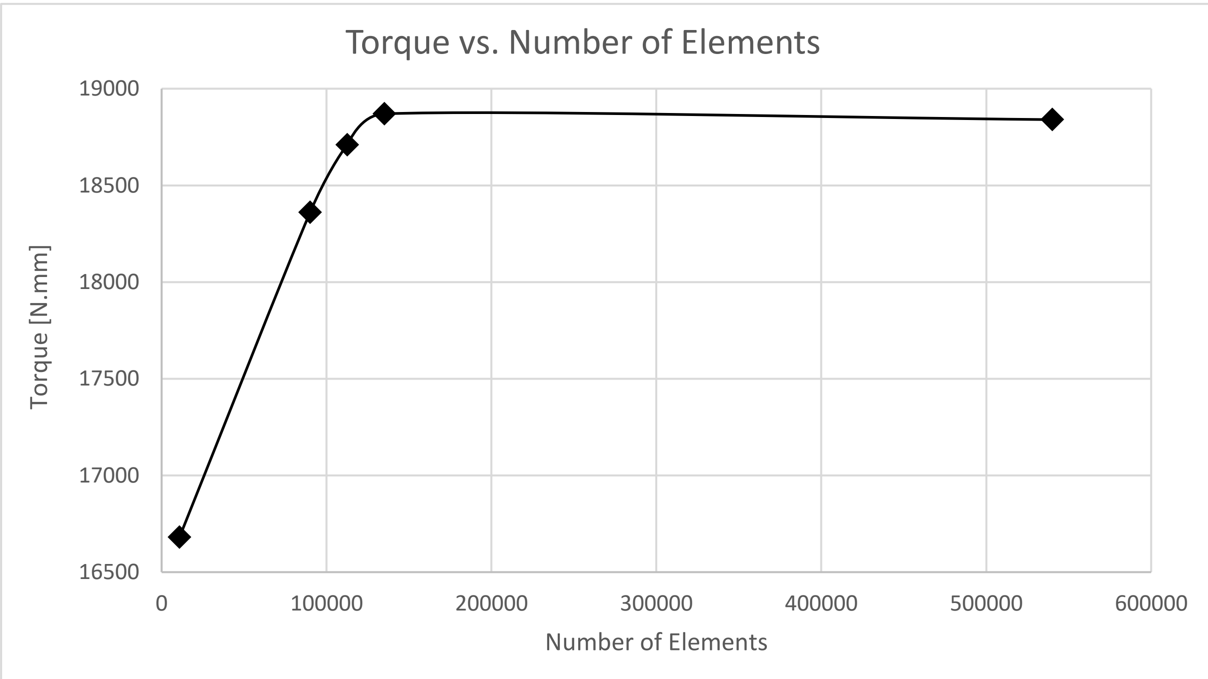
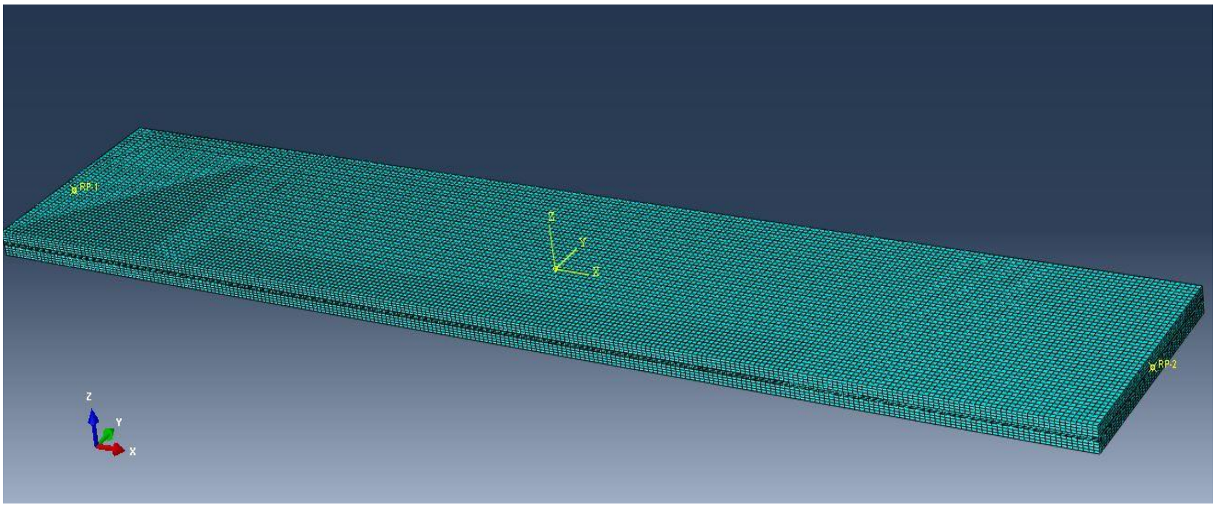
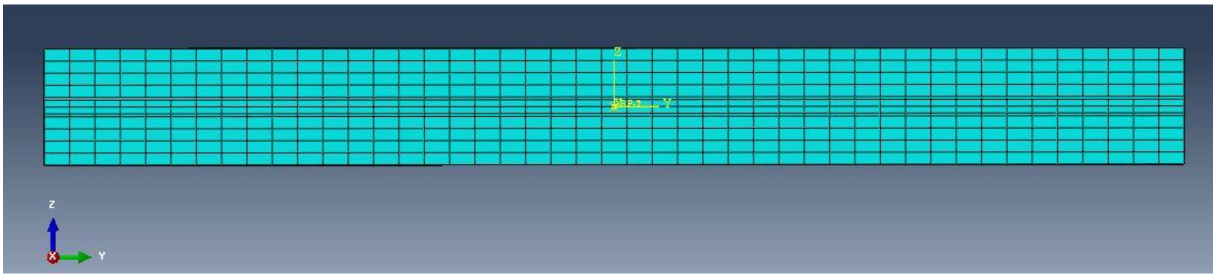


Figure 5: Mesh Convergence Study



(a)



(b)

Figure 6: Finite Element Mesh (a) Isometric View (b) Cross Section View

Calculation of Shear Strain from the FBG Strain Results

The FBG sensors are placed on the beams with ±45° from the axial direction. Strain transformation Equation (1) could be used to calculate the shear strain from the measured strain using FBG sensor.

$$\varepsilon_{fbg} = \varepsilon_x \cos^2\theta + \varepsilon_y \sin^2\theta + \gamma_{xy} \sin\theta\cos\theta \tag{1}$$

Assuming axial strain and transverse strain are small compared to shear strain, Equation (1) for $\boldsymbol{\theta} = \mathbf{45}°$ becomes,

$$2\varepsilon_{fbg} = \gamma_{xy} \tag{2}$$

The measured FBG strain will be multiplied by two to obtain the in-plane shear strain $\boldsymbol{\gamma_{xy}}$.

RESULTS AND DISCUSSION

Torque results obtained from the torsion test of the beams S1T and S2T in comparison with FEA are presented in Figure 7 and in Figure 8 respectively. Repeatability is confirmed considering the similarity between the results of the three tests. The results obtained from the FEA and from the tests are in close agreement in the range of 0° - 10° of angle of twist where the error is below ±10%. Between 10° and 20°; however, the difference between the results increases with increasing angle of twist. This may be caused by the fact that only geometric nonlinearity is included in the analyses. The results obtained from the FEA might approach to the ones obtained from the tests if material nonlinearity is also included.

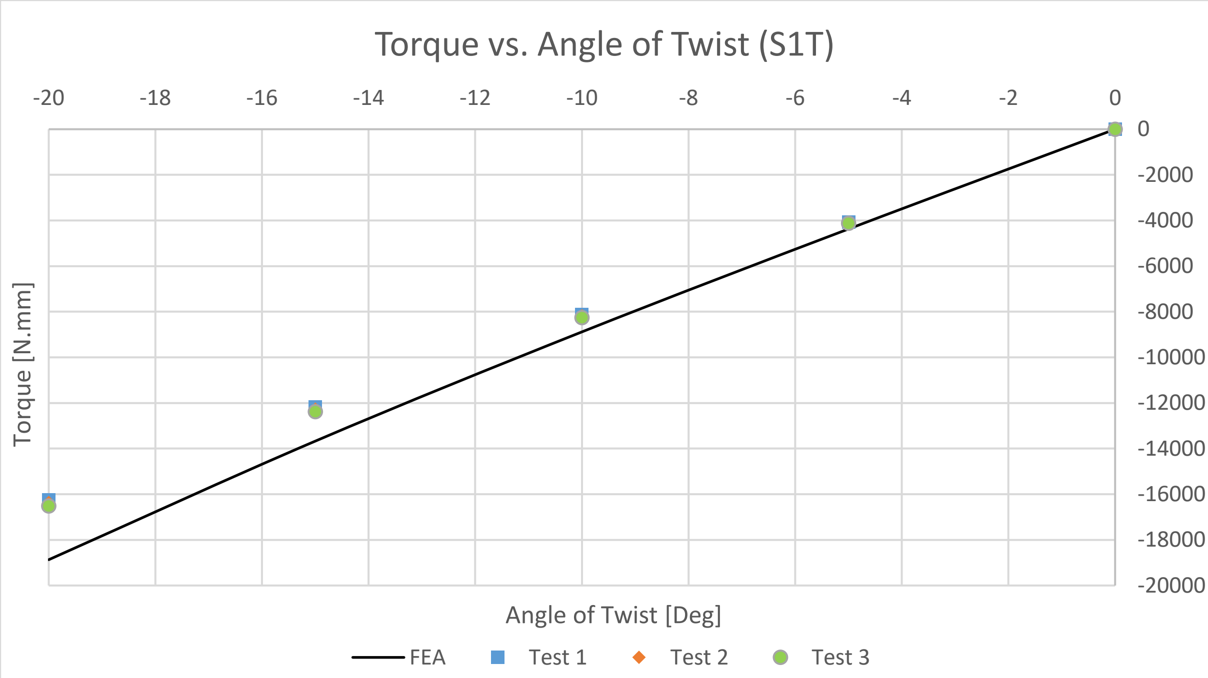


Figure 7: Torque vs. Angle of Twist for the Beam S1T

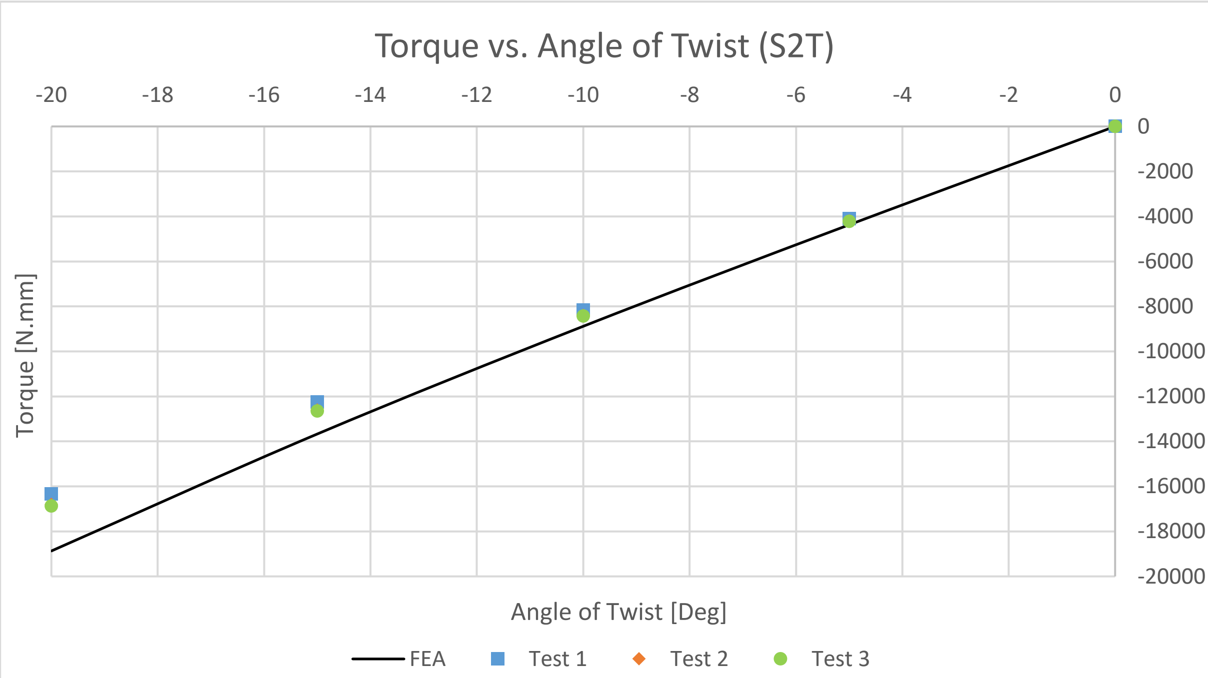


Figure 8: Torque vs. Angle of Twist for the Beam S2T

Shear strain results obtained from the FBG sensors and from the FEA are presented below. Figure 9 and 10 demonstrate the shear strain results on the surfaces of S1T for both positive and negative strain respectively. Figure 11 and Figure 12 present the shear strain results obtained from the surface of S2T and from the middle of the UD layers of S2T. From the figures, it is observed that the repeatability is again achieved. In addition, shear strain results increase with increasing distance from the middle plane of the beam, as expected. Shear strain results obtained from the middle of the woven layers of S2T are not presented since they are close to the zero, which is also expected. Furthermore, it could be seen that the difference between the shear strain results obtained from the FEA and from the tests increase with the increasing angle of twist. As before, this might be due to the fact that material nonlinearity is not included in the analyses. In addition, errors caused by human intervention during the manufacturing and the tests might also adversely affect the results. Sensors might not be at the desired positions due to the fact that alignment of the sensors is conducted by hand. Also, the positions of the FBG sensors might be altered during the curing process.

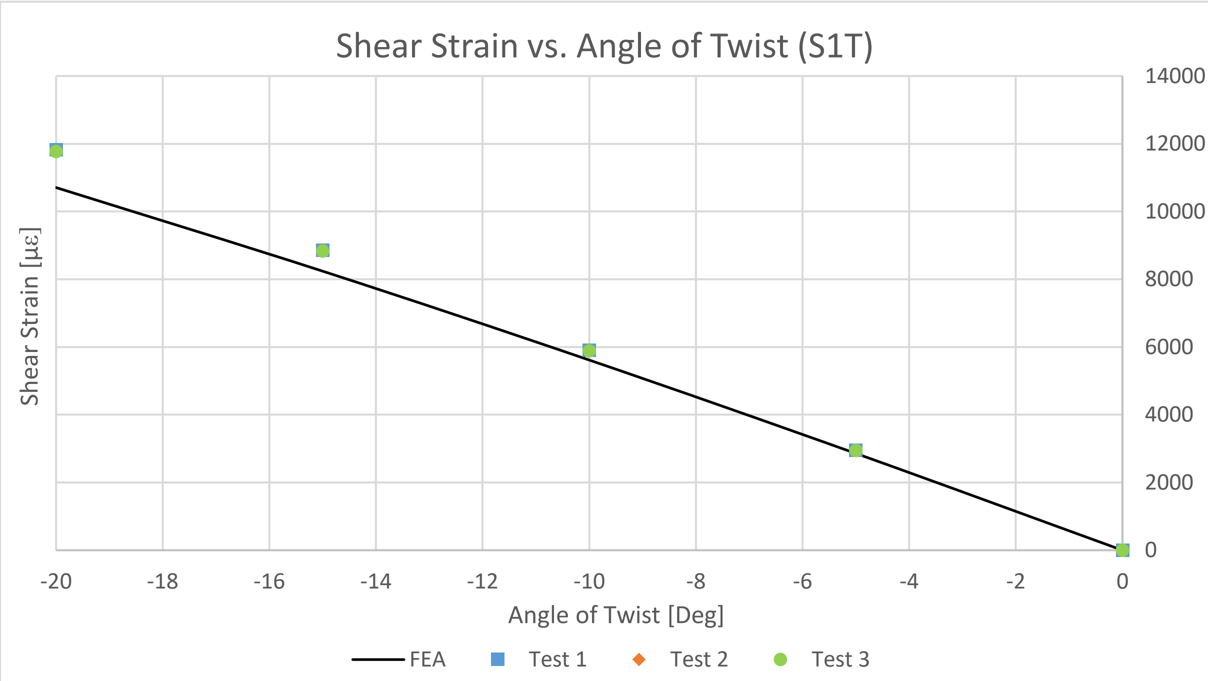


Figure 9: Shear Strain vs. Angle of Twist on the Surface of S1T (Positive Strain)

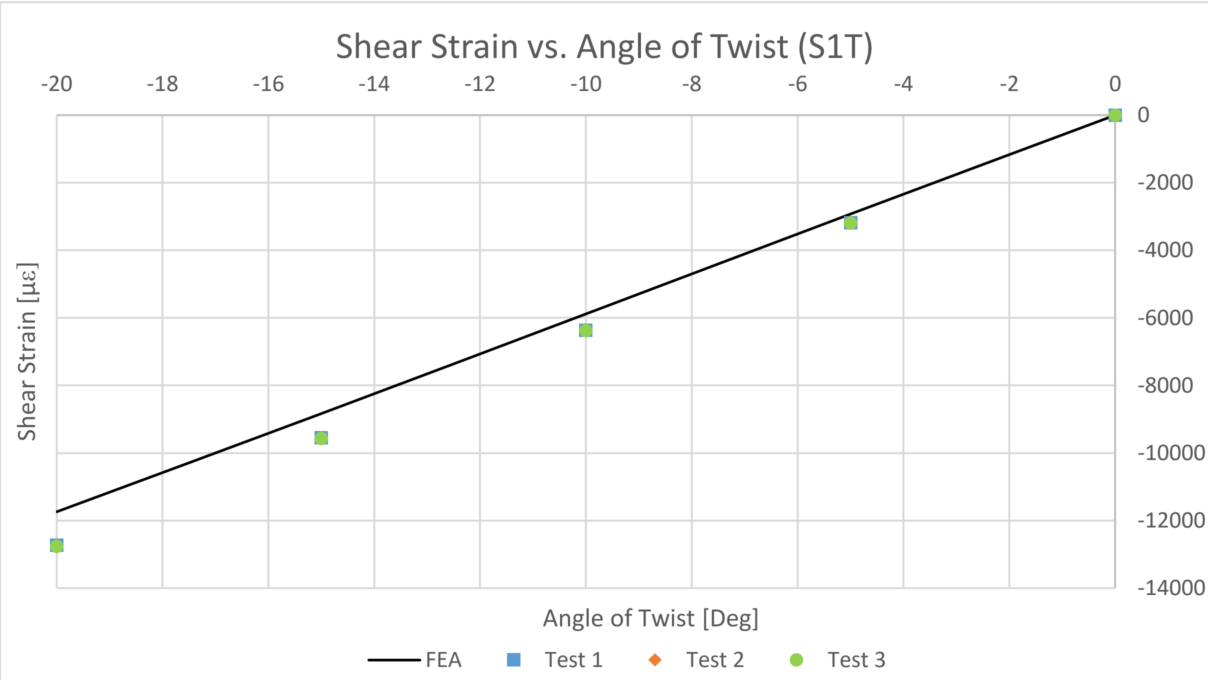


Figure 10: Shear Strain vs. Angle of Twist on the Surface of S1T (Negative Strain)

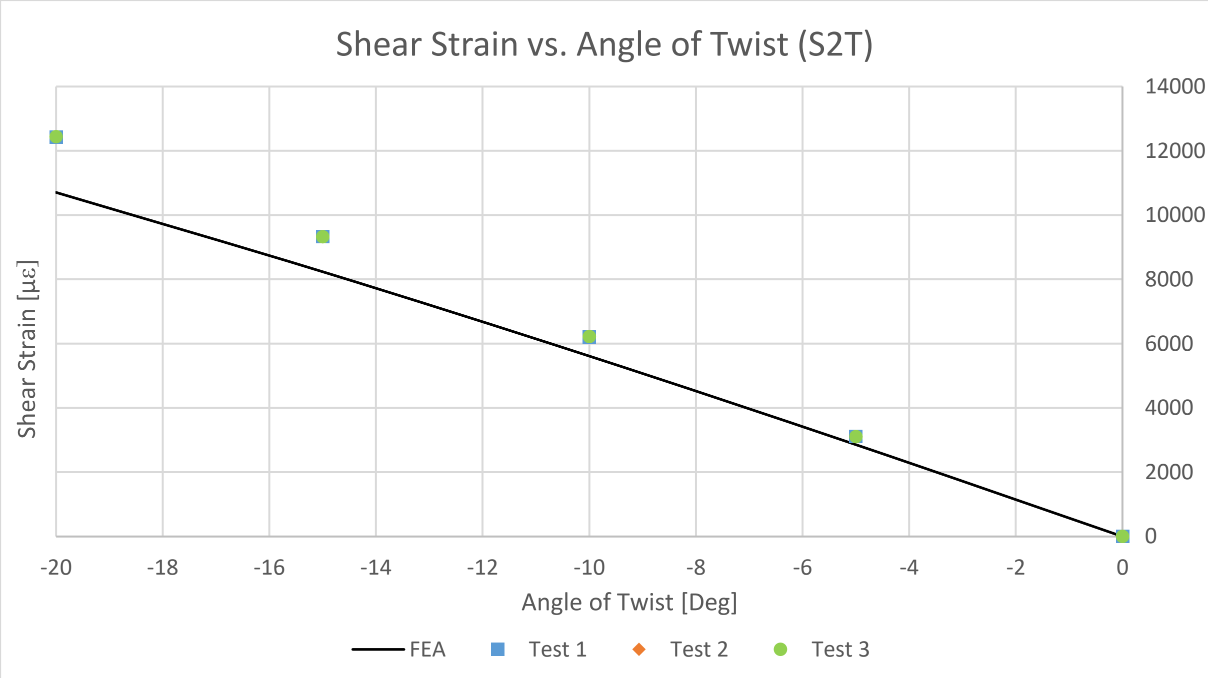


Figure 11: Shear Strain vs. Angle of Twist on the Surface of S2T (Positive Strain)

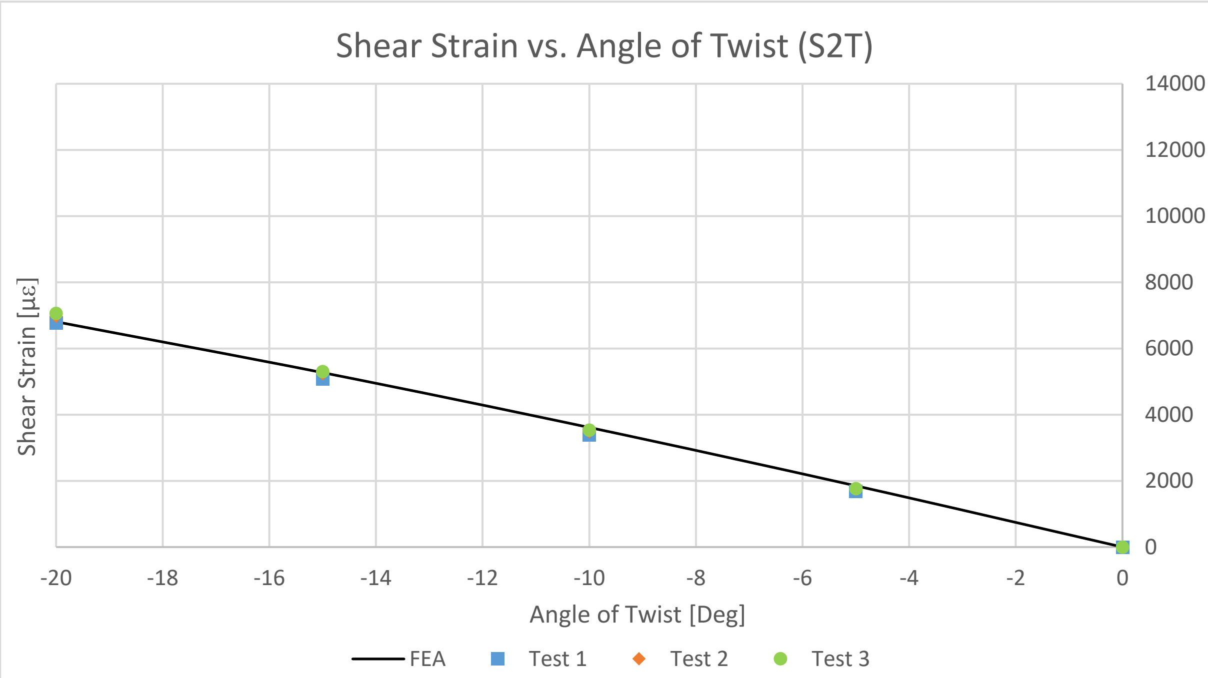


Figure 12: Shear Strain vs. Angle of Twist in the Middle of the UD Layers of S2T (Positive Strain)

Comparison of the torque measurements obtained from the load cell of the test machine for S1T and S2T are seen in Figure 13. In addition, torque vs. strain data obtained from the FBG sensors on the surfaces of S1T and S2T are presented in Figure 14. The results obtained from the two beams are close, which again proves repeatability. However, the small differences might be due to dissimilarities in alignment during mounting the beams on the grips of the test machine and small misalignment of the sensors since the measurement of the alignment angles and the bonding of the sensors are performed by hand.

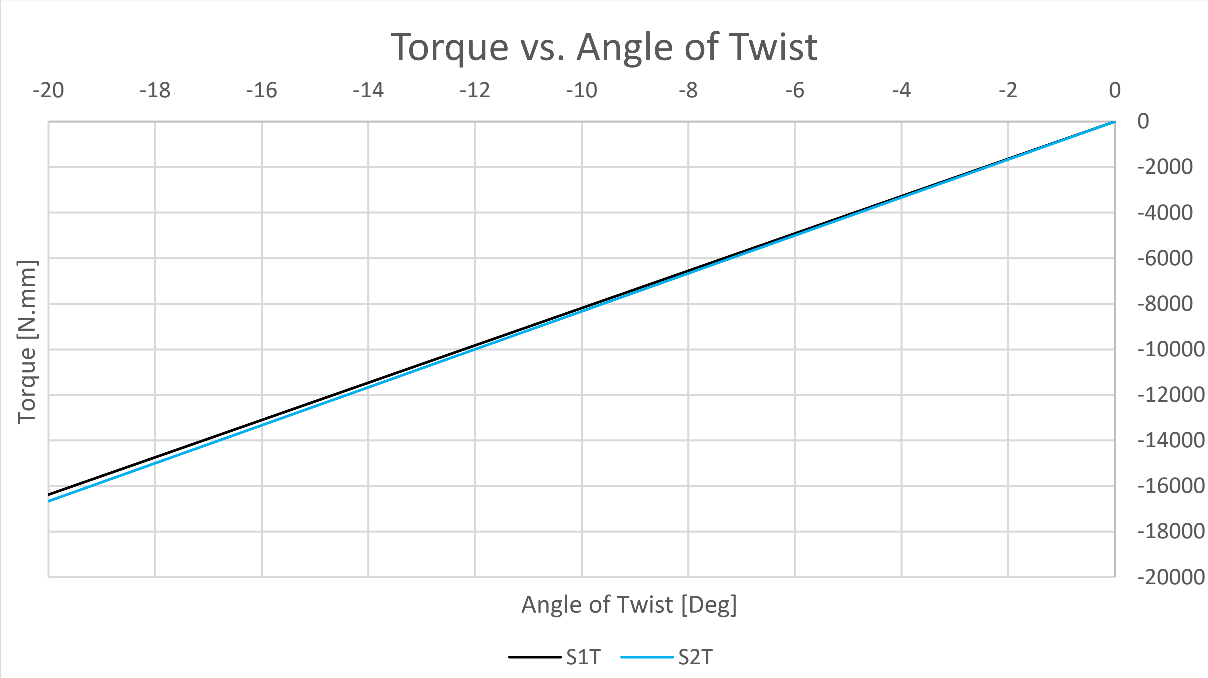


Figure 13: Torque vs. Angle of Twist for both S1T and S2T

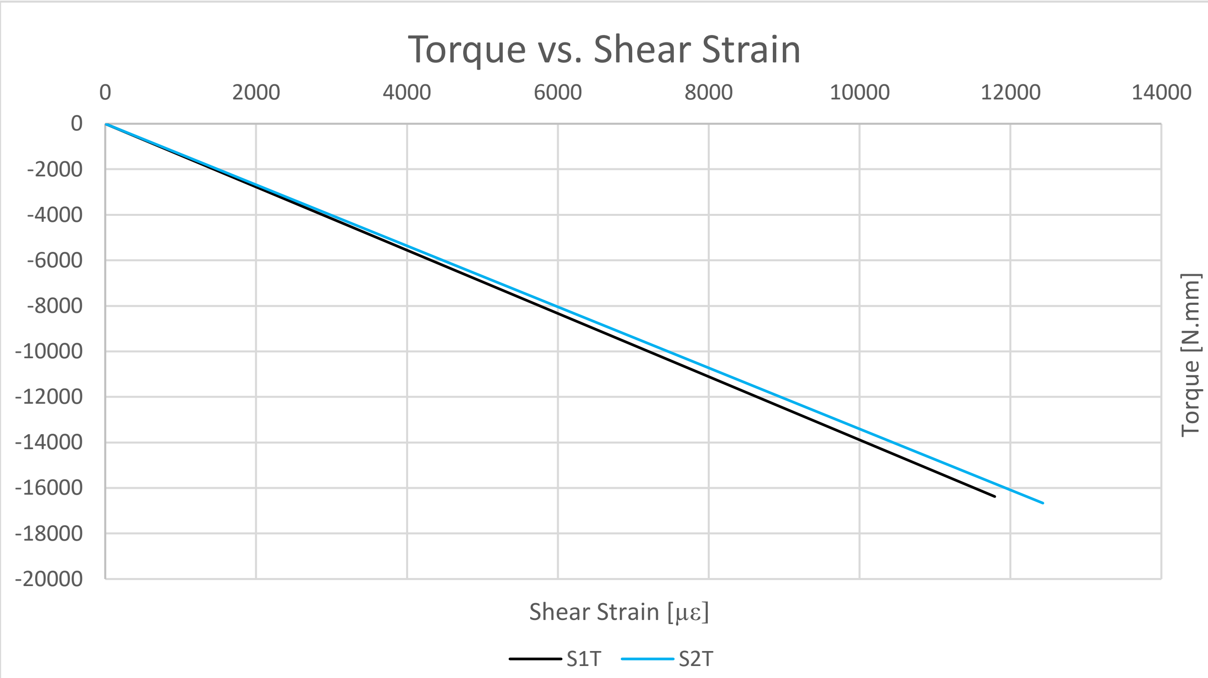


Figure 14: Torque vs. Strain Obtained from FBG Sensors on the Surfaces of S1T and S2T

CONCLUSION

FBG sensors are commonly being used to monitor the health of the composite structures. In this study, manufacturing of the composite beams with embedded sensors are presented. Teflon tubes are utilized around the fiber optic cables to avoid the breakage at the egress regions. In addition, torsion tests of the composite beams with embedded and surface bonded FBG sensors are conducted. Results reveal that there are small differences between the results of the two beams which might be caused by manufacturing faults and errors in alignment of the sensors. Further, the results obtained from the FEA and tests coincide up to 10° of angle of twist. However, the results after a 10°of angle of twist differ with increasing angle of twist. The reason behind the difference might be not including material nonlinearity, manufacturing errors and alignment errors. Comparison between the results obtained from tests and FEA indicates that FBG sensors are promising. Damage detection of composite structures using FBG sensors is considered as a future work.

ACKNOWLEDGEMENT

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