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Comparison of strain measurement methods: optical FBG sensors, strain gages & digital image correlation

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Abstract: The article focuses on a comparison of three different strain measurement methods during the tensile test: Fiber optic Bragg Grating (FBG) sensors, resistive strain gages and Digital Image Correlation (DIC). FBG sensor was embedded into the structure of composite specimen. Strain gage was attached to the surface. DIC was used for measuring surface strains. Specimen was made of Carbon/Epoxy composite. Quasi-static tensile load was applied until final damage. The results of all strain measurement techniques were compared using the calculated Young's moduli.

Keywords: Fiber Bragg Grating sensor; Strain Gage; Digital Image Correlation

1. Introduction

Resistive strain gages are commonly used to measure surface deformations. Fiber Bragg Grating (FBG) sensors provide possibility to measure both surface and internal deformations in case of composite materials. FBG sensor, which is integrated directly into the composite lay-up, is exposed to mechanical stress and high temperature during the curing process. Especially in case of prepreg/autoclave method, with high pressure and temperature, primary coating of FBG sensor can be cracked or deformed which could lead to incorrect strain transfer between composite and sensor. Strain gages (SG) and digital image correlation (DIC) were chosen as a reference for the evaluation of the strain readings from FBG sensor embedded in the composite.

2. Experimental methods

The tested specimen was made of Carbon/Epoxy composite (see Fig. 1). It was about 310 mm long with dimensions of cross-section of 30 x 2.8 mm. The composite lay-up consisted of sixteen unidirectional prepregs (± 45° orientation). Woven prepreg fabric was used for outer layers. Specimen was cured in autoclave (for three hours at 125°C ± 5°C and pressure of about 0.5 MPa). Glass/Epoxy pads were bonded to specimen ends to minimize the stress concentrations induced by grips. Configuration of sensors and strain measurement methods are described below.

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Electro-mechanic testing machine TiraTest 2300 with a maximum loading force of 100 kN was used for the experiment. The specimen was clamped at both ends in mechanic grips and loaded by quasi-static tensile force until final damage.

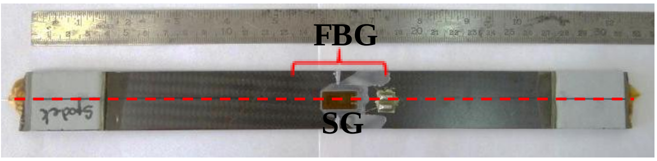

Fig. 1. Carbon/Epoxy specimen for tensile test. Location of integrated optic fiber and FBG sensor is marked by red line.

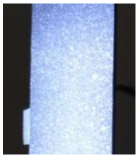

Fig. 2. Detail of a surface pattern.

2.1. FBG sensors

FBG sensor was used to measure longitudinal strain during the uniaxial tensile test. FBG sensor working principle is based on a periodical change in refractive index in a fiber optic core. This so called “grating” reflects part of the light back, the rest of light is transmitted. Mechanical loading of the material or temperature change induces a change in the Bragg wavelength which is proportional to the deformation. For a more detailed description of the method see [1]. FBG sensor (c.w. 850 nm, 8 mm grating length, 195 µm primary coating diameter, coating material: ORMOCER®) was embedded longitudinally, between the 8th and 9th prepreg layer, with measuring grid situated into the middle of the specimen (see Fig. 1). Raw optical signal was processed by the Safibra FBGuard optical measurement unit and PC unit. Relative wavelengths and reflected spectra were recorded with sampling frequency of 70 Hz.

2.2. Strain gages

Resistive strain gage was installed in a central part of a specimen. Strain gages are common sensors for measuring local surface strains. The method is based on a measuring of changes in electric resistance of a gage’s grid, that are caused by mechanical deformation of strain gage. The measurement technique is described in [2]. Strain gage (HBM 1-LY11-10/350, length of measuring grid 10 mm, nominal resistance 350Ω) was placed in a central part of the specimen (see Fig. 1) It was connected to HBM Spider8 multichannel measuring device using the three-wire quarter-bridge connection. Data were captured to PC with frequency of 50 samples per second.

2.3. Digital image correlation

2D DIC was used to measure surface strain field in uniaxial tensile test. DIC is non-contact optical method allowing material points to be tracked during a deformation (see e.g. [3] for detailed information about the method). A random surface pattern is created at first. Evaluation algorithm identifies material points in gray-scaled consecutive images of a specimen. Finally a deformation is found as the mapping between consecutive images giving the highest correlation. Commercial DIC system Dantec Dynamics Q-450 was used. It consisted of the camera NanoSense Mk III

(1.3 Mpix, Dantec Dynamics); lenses Sigma EX (105 mm, 1:2.8 D Macro, Sigma) and PC unit. Thin surface layer of acrylic lacquer (black and white) was sprayed on the specimen to create random pattern (see Fig. 2). The experiment was recorded at sapling rate 20 Hz. The object ROI 36*30 mm*mm was projected onto 1200*800 pixels*pixels.

3. Results & Conclusions

Tensile specimen broke within the resin into two pieces (see Fig. 3). Both strain gage and FBG sensor remained functional and responsive. Surface strains measured by DIC method are pictured in Fig. 4 (longitudinal direction) and Fig. 5 (transverse direction). To compare measurement methods, average longitudinal strain was calculated in two lines (see Fig. 4). Line 1 is 36 mm long and it is compared to strain readings from FBG sensor. Line 2 is 13 mm long and it is compared to strain readings from resistance strain gage.

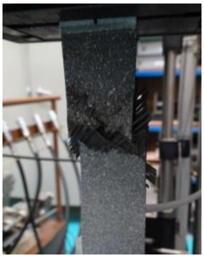

Fig. 3. Detail of tensile fracture of the specimen.

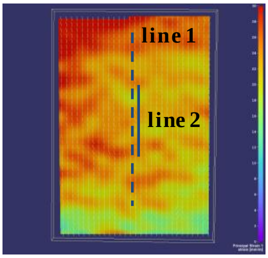

Fig. 4. Principal strains in a longitudinal direction. Lines 1&2 for evaluating strain are marked.

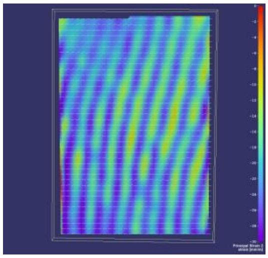

Fig. 5. Principal strains in a transverse direction.

Time course of strain readings are pictured in Fig. 6. (until the final damage).

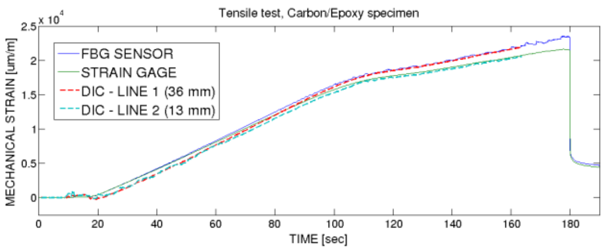

Fig. 6. Graph of indicated mechanical strain versus time.

Tensile (Young's) modulus was chosen as a suitable basis for comparison of measuring methods. Specific values were calculated from linear parts of stress-strain curves. They are listed in Table 1 (FBG sensor was taken as a reference for calculation of difference).

Table 1. Comparison of values of Young's moduli

	Young's modulus [GPa]	Difference [%]
FBG sensor	12.2	Reference
DIC - line 36 mm	12.3	0.82
Strain Gage	12.7	4.10
DIC - line 13 mm	12.4	1.64

FBG sensor provides ability to measure spectrum, reflected by it's grating (see Fig. 7). It changes with mechanical deformation (and temperature). Common spectrum shifts caused by sensor elongation can be observed, followed by distortion of the spectra (caused by multi-axial non-uniform strain field) at the initiation of the specimen damage. After unloading, specimen is permanently deformed, which is indicated by "Zero force" spectrum shift (difference between the blue and purple spectrum).

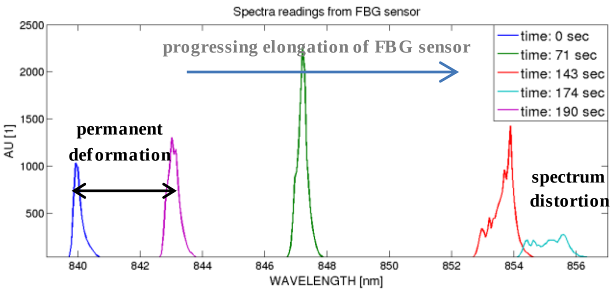

Fig. 7. Spectra readings from FBG sensor.

The experimental results quantified by the Young's moduli are in a very good agreement for all described measurement techniques. Maximum difference between the methods is up to about 4 %. It was confirmed that FBG sensor was not damaged during the autoclave manufacturing process of the composite and it measured reliably until the final damage of the specimen.

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