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Use of FBG Sensors for Delamination Growth Measurement under Mode I loading

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Abstract

This paper summarizes the experience gained during the experimental research on sensitivity of optical Fiber Bragg Grating (FBG) sensors. The sensors were embedded inside composite specimens that were subjected to cyclic loading in mode I to achieve delamination growth. Data from the FBG sensors were compared to camera readings to evaluate the ability of the sensors to detect the damage in advance. Average delamination detection advance in loaded state was 6.7 mm and 8.9 mm for the first and the second sensor, respectively. The obtained results will be used to design proposal of the sensor network for an air intake.

Introduction

The presented experimental work was focused on a sensitivity research of the FBG sensors. The technical problem to be solved is the impact or acoustic damage detection on an air intake carbon/epoxy composite structure. This structural part has no flight load bearing capacity, but it is loaded by acoustic pressure from the engine, resulting in presumed combination of mode I (opening) and mode II (shear) loading. FBG sensors are small enough to be embedded inside the prepreg composite structure. The embedding procedure was successfully tested, but there is a question of the sensitivity of such sensors in the given conditions. The first test of the damage detection capabilities of the FBG sensors was focused on the evaluation of the distance, from which can this sensor detect the delamination. Research was performed during the delamination growth testing in a mode I loading case using a double cantilever beam (DCB) specimens [1].

Experimental Method

FBG sensors are based on a periodic variation in the refractive index of the optical fiber core. When a broadband light spectrum from an optic source is guided by the optical fiber into the FBG sensor, part of the light is reflected by the grating (in a form of narrow Gaussian peak) and the rest is transmitted (more details can be found in [2, 3]). For sensing purposes, the reflected peak is commonly measured using a spectrometer. Each Bragg grating is characterized by so-called Bragg wavelength, which is shifting according to deformation of grating. The elongation causes a positive shift, shortening causes a negative shift (see Fig. 1).

However, the FBG sensors that are embedded inside the composite structure are not only stretched. They are exposed to complex non-uniform stress field because of anisotropy and microbends which can lead to a distortion of the spectrum (see Fig. 2). These two effects (shift and distortion of the peak) were used for detection of near fatigue delamination inside the tested DCB specimen.

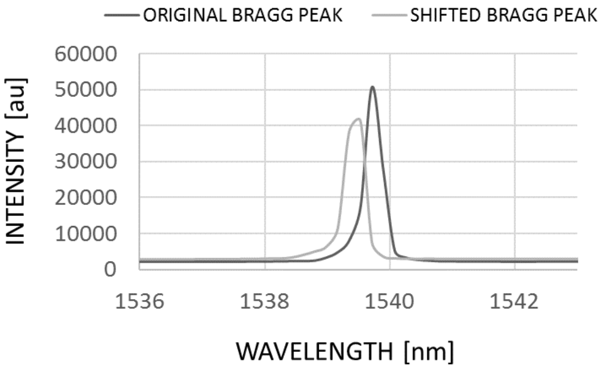

Fig. 1 Shifted peak (uniform strain) caused by pressure.

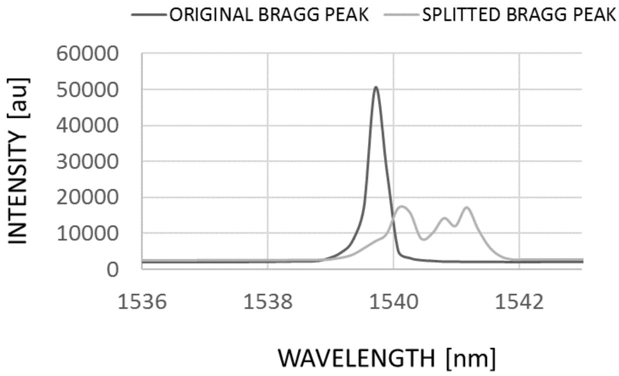

Fig. 2 Distortion of the peak caused by the complex non-uniform stress field.

So-called FBG chains were used for testing of five specimens (DCB01-05). The chains consisted of multiple FBG sensors on a single optical fiber with the following parameters: outer diameter of 0.195 mm, central wavelength of 1550 nm. Spacing between the two successive sensors was 25 mm. ORMOCER® primary coating was used.

Experimental Specimens

Carbon fibre-reinforced composite Hexply AGP 193PW/8552S RC40 with the 16 layers lay-up of $[45/0]_{4S}$ was manufactured and five DCB specimens were extracted (dimensions: 250 x 25 x 5 mm). A non-adhesive plastic foil sheet was inserted to the plate edge during manufacturing to the neutral axis to initiate the delamination growth between the 8^{th} and 9^{th} layer. Optical fibers were embedded into the composite structure between the same layers (see Fig. 3). One end of the optical fiber was led out from the composite lay-up and it was fusion spliced to the protective cable with FC/APC connector.

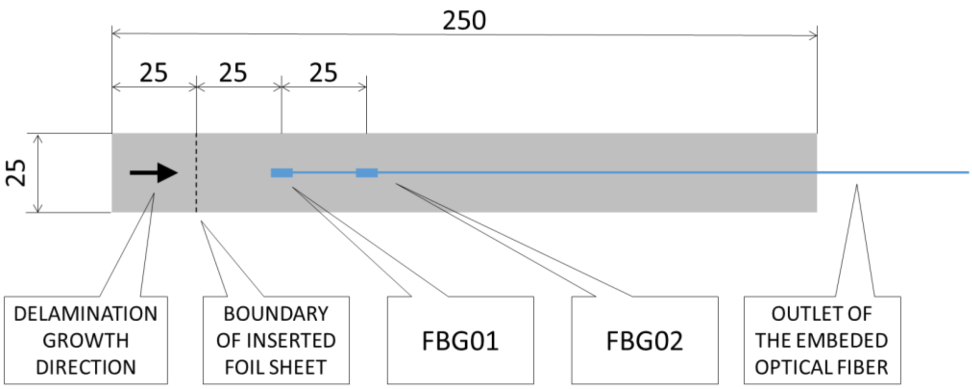

Fig. 3 Configuration of specimen and embedded FBG sensors (DCB01-05).

Experimental Procedures

DCB Specimens Fatigue Testing. The specimens were clamped using bonded aluminum blocks into INOVA ZUZ 50 loading machine, with a LTC-116-0.1 load cell, which has a capacity of 1 kN. The end of the specimen was supported by a flexible wire to maintain the specimen in the horizontal direction, and to reduce any additional forces that could originate from the specimen weight (Fig. 4).

The test was driven by displacement amplitude. The goal was to find loading conditions that will enable to test specimen within demanded time period with approximately constant crack growth rate (achieved by regularly increased displacement) and with one constant displacement cycling part included for the material properties evaluation.

The ASTM D6115 [4] is the only released standard considering fatigue delamination in CFRP and it focuses only on the crack growth onset (initiation from the insert). Therefore, the used fatigue crack growth test procedure was based on a draft standard for fatigue delamination crack growth that is being prepared for ASTM International. This procedure is well described in [5]. The displacement was zeroed at a value that corresponded with the force of 1 N. This step was performed because the displacement-controlled cycling could cause negative force values for very low displacements when the displacement would not be zeroed properly. The crack propagation during the following loading was monitored using video cameras. Sinusoidal loading with displacement control and a frequency of 5 Hz was applied. Load and displacement were recorded by the INOVA machine at a frequency of 100 Hz. The overall duration of all cyclic loading blocks was nearly 700 000 cycles. Typical fatigue crack (delamination) length propagation curve is pictured in Fig. 5.

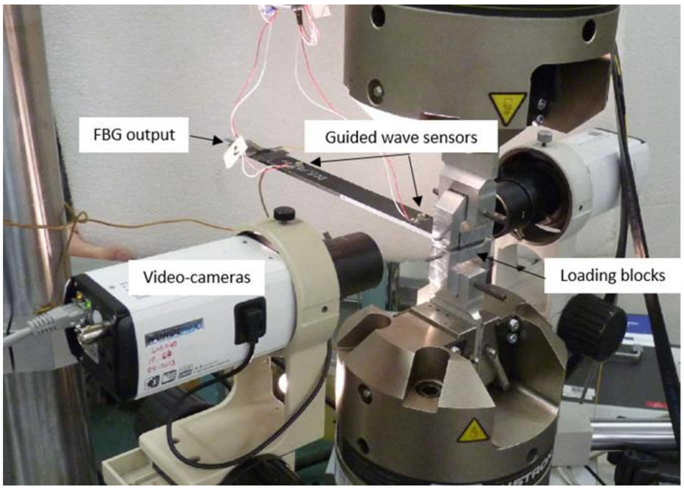

Fig. 4 Experimental set-up.

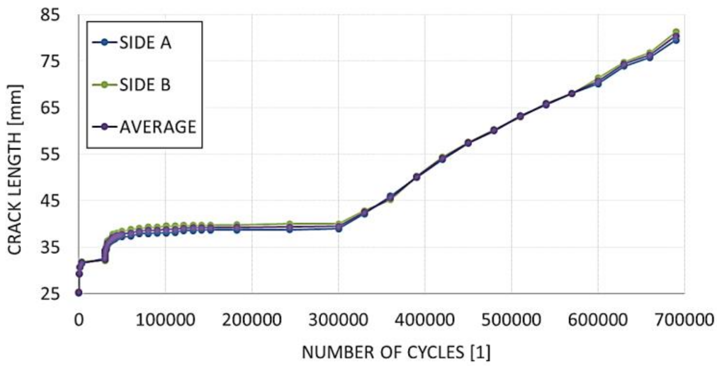

Fig. 5 Fatigue crack length propagation curve (specimen DCB01).

FBG Sensors. Safibra FBGuard 1550 DAQ device was used to capture signal from the FBG sensors. Bragg spectra during two static load cases (loaded / unloaded specimen) were recorded after the each cyclic loading block. Mechanical strain from FBG sensors versus time was also measured with data sampling frequency of 50 Hz.

Experimental Results

Analysis of the Bragg spectra for all static load cases was performed. There are two characteristic peaks, one for each FBG sensor. Damage is detected by the shift of the Bragg wavelength (as shown in the Fig. 6 for the unloaded state) of each peak and distortion of its shape (original peak is splitted into multiple peaks of lower intensity, see Fig. 7). For the number of cycles, where FBG sensor has detected damage, the actual damage length (from camera signal analysis) was evaluated. Damage detection advance (FBG sensor vs. camera reading) was calculated as a difference between the position of the FBG sensor (50 or 75 mm, measured from the specimen's front edge) and the value obtained from cameras. Results are shown in the Table 1. It can be seen that in all cases the FBG sensor was able to detect damage in composite before it reaches sensor's position. Average damage detection advance in loaded state was 6.7 mm (first sensor) and 8.9 mm (second sensor, under the higher bending stress). These values are higher than in the unloaded state (5.9 and 6.9 mm), as expected.

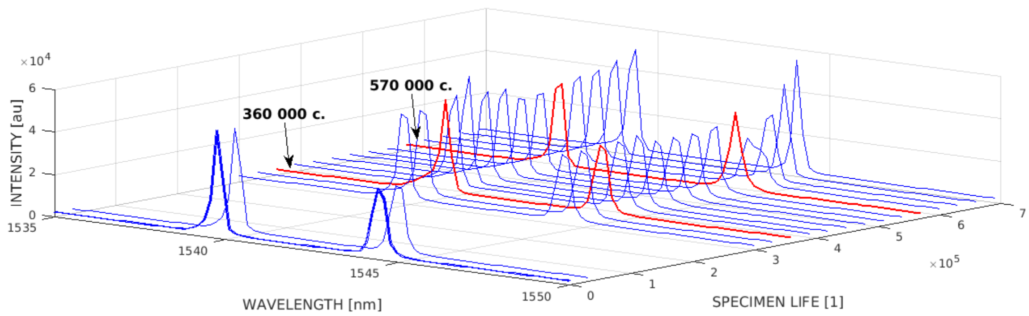

Fig. 6 Specimen DCB01 Bragg spectra reading, Unloaded state.

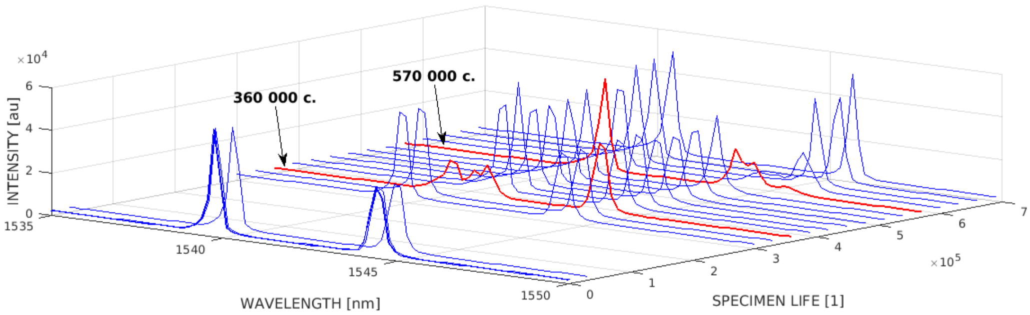

Fig. 7 Specimen DCB01 Bragg spectra reading, Loaded state.

Table 1 Summary of results for specimens DCB01-05.

	distance from specimen's front edge [mm]		50	75
DCB01	damage detection advance (FBG sensor vs. camera reading) [mm]	loaded	4.4	9.2
		unloaded	4.4	6.9
DCB02		loaded	6.4	10.0
		unloaded	6.4	8.1
DCB03		loaded	5.9	8.1
		unloaded	5.9	5.3
DCB04		loaded	9.5	7.8
		unloaded	9.5	7.8
DCB05		loaded	7.4	9.4
		unloaded	3.1	6.4
	average damage detection advance [mm]	loaded	6.7	8.9
		unloaded	5.9	6.9

Conclusions

The conducted experiment demonstrated that embedded FBG sensors are able to detect delamination in composite specimen loaded in the mode I, both in loaded and unloaded state. Average detection advance of FBG sensors before the damage is visible reaches up to 6.9 mm in the unloaded state and 8.9 mm in the loaded state. The obtained results will be used to design proposal of the sensor network for an air intake. Density of the FBG sensors will depend on minimum required detectable damage size, in combination with evaluated sensitivities. However, it is obvious that sensor density will be significant and therefore it will be necessary to monitor only critical parts of the air intake. These will be found during the full-scale demonstrator test.

Acknowledgement

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