Composites Science and Technology 154 (2018) 64–75

Contents lists available at ScienceDirect

Composites Science and Technology

journal homepage: http://www.elsevier.com/locate/compscitech

Strain pattern detection of composite cylinders using optical fibers after low velocity impacts

Bo-Hun Choi [a], Il-Bum Kwon [b, *]

[a] Department of Materials Physics, Dong-A University, Saha-gu, Busan, Republic of Korea
[b] Center for Safety Measurements, Korea Research Institute of Standards and Science, Daejeon, Republic of Korea

ARTICLE INFO

Article history:
Received 3 August 2017
Received in revised form
17 November 2017
Accepted 18 November 2017
Available online 21 November 2017

Keywords:
Structure composites
Optical fiber
Laminate
Impact behavior
Residual stress
Deformation

ABSTRACT

The strain pattern distributed on composite cylinders after impacts was detected using optical fibers for the first time. The sensing optical fiber was implemented on the composite cylinders using aluminum (Al)-coated optical fiber, polyimide-coated optical fiber, or standard single mode fiber (SSMF) of polymer-coating. The residual strain of this sensing fiber was measured by a Brillouin optical correlation domain analysis (BOCDA) sensor system, using phase modulation and single side band modulation methods. Impact events of 10, 20, and 40 J energies as barely visible impact damages (BVID) were applied on the cylinders, and these fibers were deployed on the cylinder surface, or were embedded in the cylinders. For the surface deployment, Al-coated fiber exhibited the highest residual strain due to Al plastic deformation, and the strain was three times higher than the lowest SSMF value. For the embedment deployment, these fibers were individually embedded in the cylinder, which was composed of sixteen carbon fiber reinforced polymer layers using a filament winding process. In contrast to the surface deployment, the embedded SSMF gave as high residual strain as that of the Al-coated fiber. These similar residual strains of the three embedded optical fibers suggested that they came from permanent material damage inside the material. Impact events with fiber embedment caused the optical signal in the Al-coated fiber to suffer serious additional insertion loss, but the SSMF did not show loss. So the general fiber for optics communications was successfully demonstrated as a distributed residual strain sensor to detect BVID impacts of composite materials. The strain values were maintained for at least 15 months after impact events. This residual strain sensor is economical, because special fibers like Al-coated fiber were not needed, and the sensor is efficient, because it could sense the strain for long distance, without additional impact-driven insertion loss.

1. Introduction

Impact damage on composite materials has been a serious issue in maintaining aircraft and space structures, since these materials are widely used in such structures, due to their high specific strength, light weight, and flexibility in design. In particular, barely visible impact damage (BVID) caused by low velocity impacts is becoming of high importance, because of the difficulty of detection, and the strong effect on composite materials [1–3]. BVID impacts mainly come from bird strikes, tool drops during manufacturing, or runway stones during take-off. They can leave a small level of visual damage on the surface layer, while causing damage in subsurface layers, including matrix microcracking and delamination, reducing important mechanical properties like interlaminar shear strength and compressive strength [4].

Various impact damage assessment methods for composite materials were developed using active source or passive techniques. Ultrasonic testing [5], X-ray scanning [6], and nonlinear elastic wave spectroscopy [3] are included in the former as nonconstructive evaluation methods, but they are time-consuming and labor-expensive for large surface inspection. Several methods using piezoceramic sensors [2] or mechanochromic fluorescence [4] are included in the latter, and their detection techniques are limited to real time measurement with complicated signal processing. Fiber Bragg grating (FBG) sensors have also been applied with many strong advantages, including insensitivity to electromagnetic interference, small dimensions, light weight,

---

* Corresponding author.
E-mail addresses: adamchoi@dau.ac.kr (B.-H. Choi), ibkwon@kriss.re.kr (I.-B. Kwon).

https://doi.org/10.1016/j.compscitech.2017.11.019

multiplexing capabilities, and resistance to corrosion [7,8]. FBG sensors are also compatible with the manufacturing process of fibrous composite materials [9]. However, these were used as discrete sensors with significantly confined sensing area around installed FBG sensors [10,11].

We have already suggested in a previous paper an impact damage detection system in which fully distributed strain was measured using aluminum (Al)-coated optical fiber as a sensor installed on the surface of composite material [12]. The residual strain caused by the plastic deformation of Al-coating on the optical fiber, which was bonded on a composite cylinder, was measured after impact events, so that impact trace was demonstrated to be possible in the detection system. For detecting residual strain from the optical fiber, the Brillouin optical correlation domain analysis (BOCDA) sensing technique was applied using the Brillouin scattering effect [13–15]. If the frequency difference between pump and probe lightwaves propagating in opposite directions through the optical fiber becomes the inherent Brillouin frequency of the optical fiber, the probe lightwave experiences gain transferred from the pump, and it is called the stimulated Brillouin scattering (SBS) process. This Brillouin frequency shifts in proportion to the applied strain of the optical fiber. The strain sensitivity is about 0.05 MHz/micro-strain [17]. Phase modulation and single side band modulation methods were added to the BOCDA technique to extend the measurable distance, and to achieve high spatial resolution [16,17]. So this method provided fast and accurate operation to detect the location and severity of impacts with 1 cm spatial resolution in longer than 500 m distance fiber [12].

In that experiment, a special optical fiber with Al-coating was used to measure the Brillouin frequency shift that came from aluminum having a permanent deformation, even though Al-coated fiber is expensive, and has high optical signal insertion loss [12,17]. Standard optical fiber for telecommunications was not tried for this residual strain detection purpose, because this fiber does not have plastic deformation, and composite materials attached to this fiber are supposed to be almost perfectly elastic to external impacts [18]. Nevertheless, residual strain measurement analysis according to optical fiber type is left to future research. Furthermore, the impact-driven strain on the surface and its effect on the inside of composite materials would be different, and the optical fiber location deploying on composite material surface or interior can influence the residual strain measurement. However, optical fiber embedded in composite materials has not been studied for detecting the residual strain, except for FBG embedment in a few centimeter lengths [7,19].

In this paper, the BOCDA sensor system was applied for obtaining the residual strain using a phase modulation technique for choosing the sensing position, and a single side band modulation technique for finding the Brillouin frequency shift. Three types of optical fiber, which were Al-coated optical fiber, polyimide-coated optical fiber, and standard single mode fiber (SSMF) of polymer-coating, were implemented as a distributed residual strain sensor, and their strain sensing characteristics were investigated. First, these fibers were deployed on the surface of a composite cylinder. After impact events of 10, 20, and 40 J energies, which were considered to make barely visible impact damage (BVID), the residual strains were measured and analyzed for comparison. Secondly, these optical fibers were embedded in the composite cylinders having the same stacking sequence as that for the surface deployment of optical fiber using a filament winding process. After impacts on these embedding deployment experiments, the residual strains were compared to each other for the three fiber types, and for the surface deployment experiments. Finally, the residual strain of the embedded optical fiber was again measured after 15 months to examine the mechanical reliability. If this residual strain detection by optical fiber embedded in composite materials was realized, and gave clear Brillouin frequency shifts caused by impacts; and furthermore, if standard optical fibers can be used for this purpose instead of special Al-coated fiber, our suggestion to detect impact traces by measuring residual strain using optical fiber would then be a dominant approach to detect the impact damage of composite material structures.

2. Concept of impact trace detection by optical fiber surface deployment and embedment

Optical fiber is deployed on or under the surface of composite materials as illustrated in Fig. 1. In Fig. 1 (a), optical fiber with a coating layer is bonded on the surface of composite material using an adhesive. When impact is induced on the composite material, this optical fiber is deformed with composite material. After impact, the composite material is usually recovered on its shape. However, the coated optical fiber has residual strain because the plastic deformation of the coating material on the optical fiber remains some amount of strain. This strain would be detectable. In Fig. 1 (b), an optical fiber with a coating layer is embedded in composite materials. After impact, plastic deformation of the coating material could leave residual strain as for the surface bonding case, but the strain magnitude could be different. The former is influenced by only the bonding layer of the composite material, but the latter is influenced by residual strains of all composite materials. In brief words, this impact trace detection concept can be effectively accomplished under the condition that the spatial and strain resolution is enough to be sensitive to the change of residual strain distribution by impact.

3. Principle and setup of optical fiber strain detection using the BOCDA sensor system

Fig. 2 presents a schematic of the experimental setup for the BOCDA measurement system. A Distributed Feed-Back Laser Diode (DFB LD) of 1553 nm peak wavelength was used as a common source for probe and pump, and was externally modulated by an electro-optic phase modulator. A binary pseudo random bit sequence (PRBS) of $2^{15}-1$ was applied to this modulator using a pulse pattern generator (PPG). The length of this PRBS corresponded to the distance between correlation peaks induced by the interaction of two lightwaves. A single correlation peak should be located on an optical fiber sensor, and the PRBS length was calculated to measure more than 500 m optical fiber distance. For this long distance with fine spatial resolution, phase modulation of a light source was used [17], unlike a conventional frequency modulation method for BOCDA measurement [20]. Phase modulated lightwaves kept Brillouin gain on the correlation peak position longer than the SBS lifetime, even though the correlation peak position was very narrow for fine spatial resolution. The correlation peak position was decided by the bit rate of 2.5–3 Gb/s.

The modulated light was divided for lightwave generation of both the probe and pump in the system. The probe was again modulated by a single side band (SSB) intensity modulator, which suppressed the main and the first high frequency side bands, and only generated the first low frequency side band. The frequency-shifted probe had the difference of ~11 GHz from the pump, and the proper frequency difference caused the probe to earn SBS gain transferred from the pump at the correlation peak fiber position. From scanning this frequency difference, the SBS gain spectrum was obtained, and its peak is called the Brillouin frequency, which is an intrinsic material property, and changes according to strain variation. The frequency-shifted probe went through 7 km SSMF as a delay line, which was needed to design a proper correlation