Composites Part B 123 (2017) 124–135

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb

Real-time detection of low-velocity impact-induced delamination onset in composite laminates for efficient management of structural health

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ARTICLE INFO

Article history:
Received 20 March 2017
Received in revised form 6 April 2017
Accepted 7 May 2017
Available online 8 May 2017

Keywords:
Composite laminates
Low-velocity impact
Delamination
Fiber Bragg grating sensor

ABSTRACT

Carbon fiber reinforced polymer (CFRP) laminates have been becoming primary structures in the aerospace industry because of their high specific strength and stiffness. However, CFRP laminates have susceptibility to low-velocity impact events which can easily induce internal or hidden damages such as delamination. Such impacts frequently arise during maintenance, flight operation or in-service events. Thus, composite structures have to be irregularly inspected in addition to the periodic maintenance for ensuring the structural health. However, such irregular inspections can inherently incur the overall maintenance cost because it has to be performed in all suspicious cases of damages. For this reason, the methodology for accurately realizing the onset of delamination induced by low-velocity impact events is required for reducing the operating cost of composite structures. In this paper, the potential of using high speed fiber Bragg grating (FBG) sensing system for detecting the delamination onset was studied for thick CFRP laminates. Because FBG sensors can be simply multiplexed to capture the structural responses, the proposed method in this study can be quite attractive for an efficient impact monitoring system. To obtain the impact response signals and contact force histories, several low-velocity impact experiments were performed in a range of 1–30 J. From the signal processing of these experimental data, the meaningful damage index was introduced using the detail components of wavelet transformed sensor signals. Although this result is in the preliminary step, such damage index can be useful for applying an in-situ impact damage assessment system to the real composite structures in the near future.

1. Introduction

Carbon fiber reinforced polymer (CFRP) laminates have been widely used in various application fields including the aerospace, automobile, marine and civil structures because of their excellent properties such as high specific strength and stiffness, corrosion resistance, low thermal conductivity, design flexibility and so on. Also, in these days, multi-functional composites [1–3], which have not only the mechanical properties but also other thermal or electrical properties by adding a small amount of nanoparticles, have been actively studied by numerous researchers. However, they still have some limitations for more widespread uses due to their weakness for low-velocity impact events. CFRP laminates have low transverse tensile and interlaminar shear strengths compared with their high in-plane properties [4]. In addition, impact loads generated by low-velocity impact events could deliver high shear and transverse stresses to CFRP laminates. Thus, delamination can be easily induced between the various lamina by low-velocity impact events, and is notorious because such damage cannot be easily detected by traditional visual inspections. According to this weakness of composite laminates, relevant researches [5–8] about low-velocity impact damages consistently grow in importance.

In order to improve the impact resistance of polymer composite laminates, many researchers tried to enhance the properties in the through-thickness direction by using tougher matrix systems [9], 2D and 3D woven materials [10,11], stitching [12–15] and Z-pinning [16–20] and so on. Greenhalgh et al. [21] reviewed the

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http://dx.doi.org/10.1016/j.compositesb.2017.05.019
1359-8368/

above mentioned material concepts for improving the impact damage tolerance, and recommended Z-pinning and 3D woven materials for future composite structures. These methods offer good solutions to improve the delamination toughness and impact damage resistance, but many factors has to be carefully considered [21] such as the in-plane properties reduction, thickness increase, redesign and requalification, application cost and so on.

As the other trials to handle the impact-induced delamination in laminated composites, studies about detection of low-velocity impact events and evaluation of damage severity have been steadily performed. The major concern of these studies is to develop rapid and accurate inspection techniques for efficient maintenance and safe operation of composite structures. Various types of advanced non-destructive inspection (NDI) methods [22–25] showed the great accuracy of detection and quantification of impact-induced damages inside the composite laminates. Unlike the traditional NDI methods, the required time and cost has been reduced by the advanced facilities, data processing methods and high computation power. However, they still have challenges for inspecting large-sized structures such as aerospace vehicles, civil infrastructures and so on. Due to this reason, a real-time impact monitoring system can be a promising solution for enhancing the efficiency of inspection process. Such a real-time monitoring system could offer the information about low-velocity impact occurrences and damage suspicious regions. Besides low-velocity impact events, various structural data about strain, vibration or fatigue can be achieved from the in-situ monitoring system. This information obtained from processing the real-time monitored data can dramatically enhance the usefulness of advanced NDI methods.

For a real-time impact monitoring, numerous authors have studied detection and quantification of low-velocity impact damages. Basically, in order to capture the responses from low-velocity impacts or damage occurrences, the measurement of acoustic emission (AE) signals is essential. Thus, most of researches about impact damage assessments have used piezoelectric transducers (PZT) for detecting the impact-induced waves or generating guided waves. Sultan et al. [26] suggested the potential damage indices using the features of numerous data from PZT sensors by employing the concept of discordancy from the statistical discipline of outlier analysis. Zamorano et al. [27] presented a novel damage parameter-based technique for passive high-speed impact damage assessment using a network of PZT sensors. Nardi et al. [28] investigated the detection of delamination in CFRP laminates using auto-regressive models obtained from the structural responses. They used a couple of PZT patches for actuation and sensing purposes. Guided ultrasonic waves have proved their effectiveness for inspecting hidden delamination damages through a number of published results [29–34]. They use the various changes of Lamb waves due to the delamination damage such as amplitude, traveling time, interference with reflected waves, scattering, mode conversion and so on. Leckey et al. [33,34] performed delamination detection and quantification with Lamb waves induced by PZT sensors and wavenumber analysis through the scanning laser Doppler vibrometer measurements.

In this paper, we propose delamination occurrence detection through a high speed fiber Bragg grating (FBG) sensing system. Compared to PZT sensors, optical fiber sensors have inherent limitations for detecting AE signals due to their low sensitivity and narrow bandwidth. However, these sensors have the advantages of light weight, small size, immunity to electromagnetic interference (EMI) which can overcome the disadvantages of high performance electrical sensors. Especially, FBG sensors are capable of multiplexing measurements, so they can cover a large area of target structures with a small number of optical fiber lines. Thus, many researchers [35–42] have tried to apply optical fiber sensors to quantify the impact-induced damages in various structures. Riccio et al. [35] investigated the delamination buckling and growth in a stiffened composite panel using the embedded optical fibers. Kim et al. [36] used a gold-deposited extrinsic Fabry-Perot interferometric (G-EFPI) sensor to detect matrix cracks and fiber breakages on composite specimens. Bang et al. [37] quantitatively evaluated the onset and damage level of matrix cracks using embedded EFPI and FBG sensor systems. Lee et al. suggested multipoint AE sensing methods using a narrowband tunable laser (NTL) and fiber acoustic wave grating (FAWG) sensors [38], and pressure-coupled FBG sensors with a lasing wavelength stabilization method [39], respectively. Xu [40] used an optical fiber interferometric sensor as an ultrasonic receiver, and successfully captured the presence of delamination of I-section composite beam. Wu et al. [41] demonstrated the potential of a phase-shifted FBG sensor to detect AE signals, and Yu et al. [42] performed the identification of damage types in CFRP laminates using this type of sensors. In this way, recent researches have been overcoming the limitations of optical fiber sensors for the quantitative analysis of AE signals.

However, in order to cover a large area, the estimating cost for constructing such fiber optic systems is still much higher than the cost of PZT sensor systems. To solve this issue, the cooperative applications of optical fiber and PZT sensors are required to supplement their individual weakness. Firstly, optical fiber sensors continuously monitor the impact events and damages over the entire structures. Then, more accurate damage evaluation schemes using PZT sensors are applied as the second step. For an efficient optical fiber sensing system for the overall impact monitoring, the high speed FBG interrogation system (SFI-710, Fiberpro Inc., Korea) can be adopted. This interrogation system has a relatively low sampling frequency of 100 kHz compared with other AE measurement systems, but it shows a remarkable multiplexing capability (over 4 points). The authors demonstrated the potential of this interrogation system to identify the impact locations on the large area of composite structures [43–47]. Then, an impact-induced delamination onset detection using the AE signals through the high speed FBG sensing system is studied in this paper for offering the reliable information to the advanced NDI methods. The focus is to develop a passive damage evaluation method in a thick CFRP laminate subjected to low-velocity impacts. From the data processing of the impact-induced signals acquired by the FBG sensors, a valuable damage index is proposed to indicate the delamination occurrences. Also, the validations of this proposed damage index are performed by using the acquired signals from multiplexed sensors and different incident angles. The authors believe that the results of this study can be a helpful solution for managing the notorious delamination damages in CFRP composite laminates.

2. Experiments

2.1. Experimental setup

Fig. 1 shows the experimental setup to perform the low-velocity impact fracture tests for developing the damage assessment algorithm. The test specimen is a 195 $\times$ 195 mm^2 CFRP composite laminated plate which was fabricated using a graphite/epoxy prepreg (USN 175BX, SK Chemical Co. Ltd., Republic of Korea). The mechanical properties of this prepreg material are listed in Table 1. The stacking sequence is $[45/90/-45/0_2/-45/0/90/0/-45/0/45/90/-45/0]_s$ for a quasi-isotropic plate and the thickness is about 5.1 mm. The dimension of test section is 180 $\times$ 180 mm^2, and four edges are fully clamped. The impacts are given by an instrumented low-velocity impact test fixture to prevent dual impacts. The impactor has a hemispherical tip with a diameter of 12.7 mm, and can