Real-Time Evaluation of Impact Induced Delamination in UAV Composite Structures Using Fiber Optic Sensors

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ABSTRACT

This study focuses on detection and evaluation of low-velocity impact induced delamination in the thick CFRP laminates used in main structures of UAVs. When the low-velocity impact occurs on the structure during operation or maintenance, acoustic emissions are generated, which are important clues for detecting and evaluating damages caused by the impact. In particular, the real-time detection of delamination using on board sensors is essential for safe operations of structures because the delamination is invisible and hard to be detected by conventional nondestructive methods.

In this study, fiber Bragg grating (FBG) sensors were used for measuring the acoustic emission signals generated from the impact. Test articles are CFRP laminates with the thickness of 5 mm, and the FBG sensor was surface attached on the bottom surface of each specimen. The low-velocity impact was given to each specimen with different energies by controlling the drop height. The acoustic emission signal in each case of different impact energy was captured by the FBG sensor in the sampling frequency of 100 kHz. This sampling speed is fast for FBG sensors, but is generally considered to be a limited speed for damage evaluations. By C-scan inspections after low-velocity impact experiments, delaminations were found in the impacted specimens over the impact energy of 15 J.

The measured signals have a form in which the main waveform generated by the structural deformation and the acoustic emission signals are mixed. The signal processing method is proposed for detecting and evaluating the delamination using such measured signals from FBG sensors. This method consists of two steps: delamination detection and delamination area prediction. Strong acoustic emission signals from the delamination occurrence affect the waveform of the measured signal, so the delamination could be detected by analyzing the symmetry of the main waveform of the measured signal. Through this first process, signals that are determined to have been damaged are selected. As the next step, the delamination areas were estimated using the induced peaks of acoustic emission signals during generating the delamination in the laminates. In this study, the delamination areas were measured by a linear regression

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using the counted numbers of peaks related to delamination. As a result, the delamination area could be reasonably evaluated using the method proposed in this study. Through this study, a useful method for a real-time delamination diagnosis with a simple optical fiber sensing system was proposed, which is considered to be a practical impact damage monitoring system applicable to real composite structures.

INTRODUCTION

Laminated composite structures have been widely used for many applications including aerospace, automobile structures [1] and various infrastructures [2]. Composite materials have many advantages over conventional metallic materials such as high specific strength and stiffness, design flexibility, low production cost and so on. Thanks to these advantages, they have been actively applied as the primary structures of UAVs in recent years. Over medium-sized UAVs, laminated composites have been adopted for the main load carrying structures like the spars, side beams, frames, skins and so on. Also, the leaf spring type landing gear using laminated composites showed excellent ground load absorbing performances.

However, composite laminate structures also have weaknesses due to the characteristics of their fabrication method by stacking each lamina. In particular, the delamination induced by low-velocity impact events is notorious for composite laminates [3] because it is difficult to detect by conventional inspection methods. Such damage gradually deteriorates the mechanical properties and eventually causes the structure to collapse, which poses a critical threat to the whole structure. Thus, it is necessary for the safe operation of composite structures to detect low-velocity impact events and perform rapid inspections for damages only in suspected areas in ground. Research in related fields has been actively conducted over the past few decades, and the number of cases applied to real structures is increasing.

This study introduces the real-time damage detection process about a low-velocity impact event using the signals obtained from a fiber optic sensor. Signals used for development and validation of the damage detection algorithm were measured by the fiber Bragg grating (FBG) sensor and high-speed sensing system. Through analyzing the obtained signals in intact and damaged cases, a method of immediately determining the presence or absence of damage was devised. Also, damage evaluations were tried by utilizing the characteristics of the damaged signals. The damage detection and evaluation method in this study can be useful for practical applications in real structures because the measurement system is quite simple [4] and the algorithm is robust to operational environments.

EXPERIMENTS

The experimental set up in this study consists of a laminated composite specimen with an FBG sensor attached to the surface, the commercial high-speed FBG interrogation system (SFI-710, Fiberpro Inc., South Korea), a low-velocity impact test fixture. The thickness of the specimen is 5.1 mm (a quasi-isotropic laminates with 30 plies), and the dimension of the test section is 180 x 180 mm^2. An FBG sensor with a grating length of 5 mm was bonded to the bottom surface of each specimen. The sensor is 50 mm away from the center of the specimen, which is the impact location. The changes of center wavelength of an FBG sensor due to an impact event were captured by the high-speed FBG interrogator with the samling speed of 100 kHz. Low-velocity impact was applied to each specimen in a free-fall manner from 1 to 30 J by adjusting the drop height. Through the C-scan inspections of all impacted specimens, the delamination damages were found over the impact energy of 15 J [5].

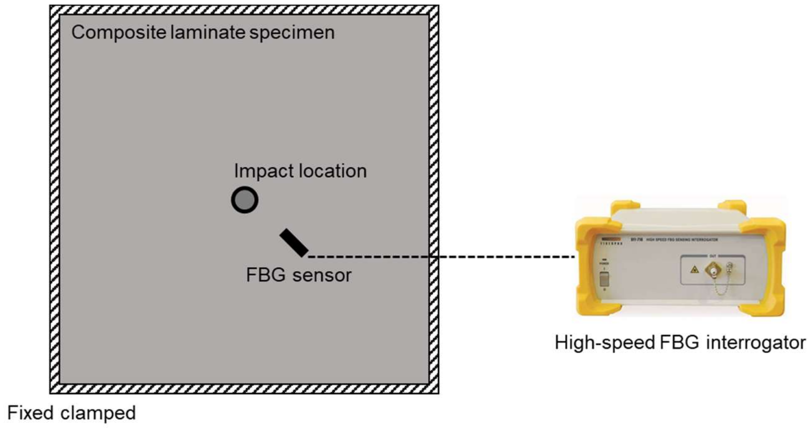

Figure 1. Experimental set up for low-velocity impact test.

DAMAGE DETECTION AND EVALUATION METHODS

The obtained impact signals from 5 and 20 J are shown in Figure 2 as the representative signals of intact and damaged cases, respectively. In the signals of intact cases, there are only fluctuations to be observed along the main wavelength shift. Such fluctuations were induced by structural vibrations from a low-velocity impact event. In the damaged cases, high frequency portions and large peaks were generated by the acoustic emissions from delamination occurrences.

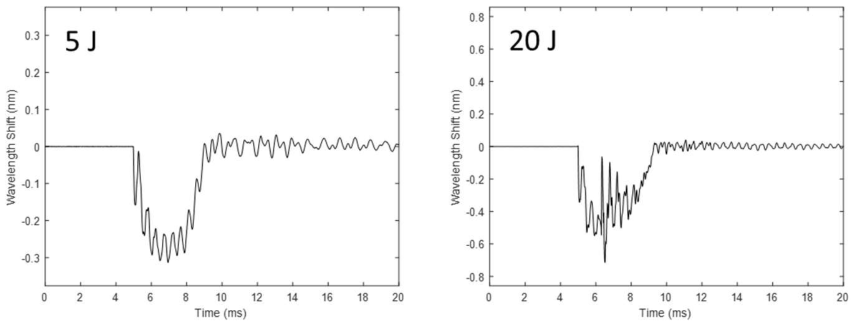

Figure 2. Impact signals in intact and damaged cases.

It is possible to examine these differences that appear in signals directly by humans and determine whether there is damage, but appropriate signal processing method is required to automatically determine damage occurrences in real-time after detection of low-velocity impact events. In this study, the fitted curves from the original signal with different orders (2nd and 4th orders) are used for detecting the differences between the intact and damaged signals. In the intact signals, two fitted curves are almost similar each other, because there are no sudden changes in the original signals. However, there are apparent differences in two-fitted curves of damaged signals depending on the fitting orders. The differences between the 2nd order and 4th order fitted curves can be evaluated from the root mean squared (RMS) value between the two curves. In the intact cases, it was found that the RMS values between two fitted curves were close to 1, whereas in the damaged cases, the RMS values decreased to 0.93 or less. From these results, it can be confirmed that it is possible to immediately analyze the impact signals to decide delamination occurrences in real-time.

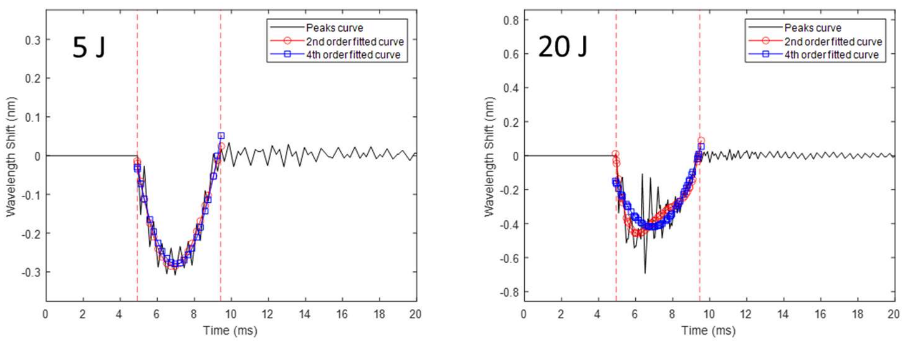

Figure 3. Fitted curves of impact signals in intact and damaged cases.

The next step is to evaluate the delamination area according to different impact energies from signal processing of impact signals. In this study, it is not easy to assess the delamination areas due to low resolution and sampling frequency of the measurement system. In order to evaluate the delamination areas, the high frequency portions by the acoustic signal emitted from the damage occurrences were analyzed. From the analysis of these portions, it can be found that the path lengths between the adjacent peaks near the damage occurrences are quite shorter than others. It means that the number of such peaks which have short path length can be increased due to the severity of damages induced by impacts. However, any peaks which have path lengths with large differences are not found in the signals of intact cases.

To decide the threshold value for counting the path numbers which have the short lengths related to the damages, numerous values were assessed as a ratio to the average of the total peak lengths in each signal. In order to find the appropriate ratio value, various plots were obtained between the damage index and delamination areas as shown in Figure 4. The damage index is calculated by dividing the number of short path lengths by the number of total path lengths.

Figure 4 also shows each R^2 value as a result of linear regressions in all cases. The closer the R^2 value is to 1, the more accurate the damage area can be assessed. In this study, 0.8629 is the highest R^2 value. Although this value may be considered relatively low compared to other studies, it is sufficient to judge the tendency of the damaged area changes according to different impact energies. Since the magnitude of delamination area is a major factor in determining the structural health in an operating situation, this can be a useful result that can estimate the delamination areas caused by an impact in real-time.

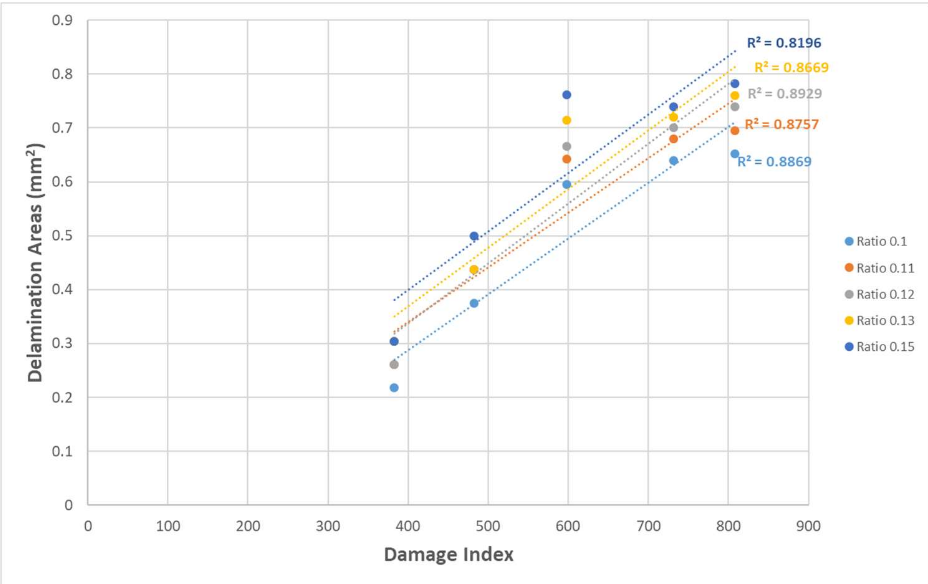

Figure 4. Damage indices versus delamination areas in different ratios.

VALIDATION

The damage detection method proposed in this study was validated from the experiments about a full-scale wing box structure. The damage evaluation method could not be validated because it needs more experimental data to obtain the appropriate threshold ratio value. In the experimental set up for validations (Figure 5), the same FBG interrogation system was used, but the test section (400 x 400 mm^2) is on the upper skin of the wing box and four multiplexed FBG sensor array was adopted for measuring the impact signals. The upper skin of the wing box structure is also a laminated composite structure, and there are several stiffeners and a rib in the test section.

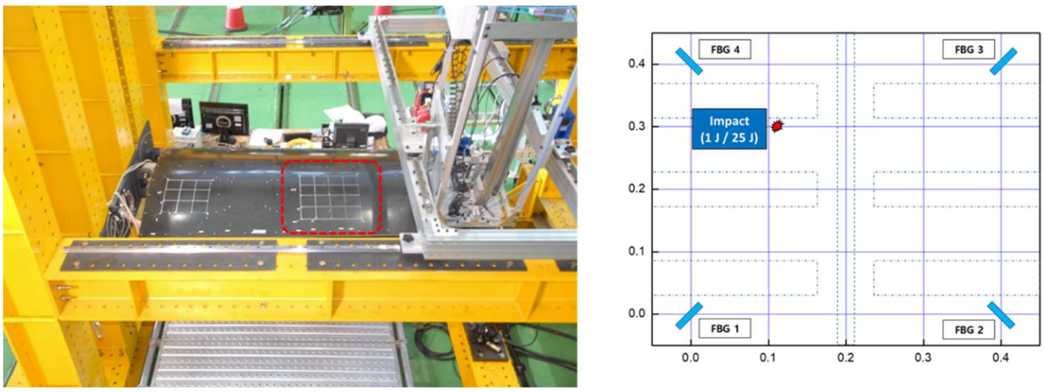

Figure 5. Experimental set up for validations.

Figure 6 shows the impact signals of FBG sensor 2 in the intact and damaged cases, respectively. In these signals, the same characteristics as the impact signals in the previsous experiments could be found. In order to validate the usefulness of the proposed damage detection method, the RMS values were calculated between the 2nd and 4th order fitted curves in both cases. Then, it can be found that the RMS value decreased to a number much lower than 1 when damage occurred. It was confirmed that the same result was obtained with all other sensor signals. From these results, the proposed damage detection method was successively validated about the full scale structure.

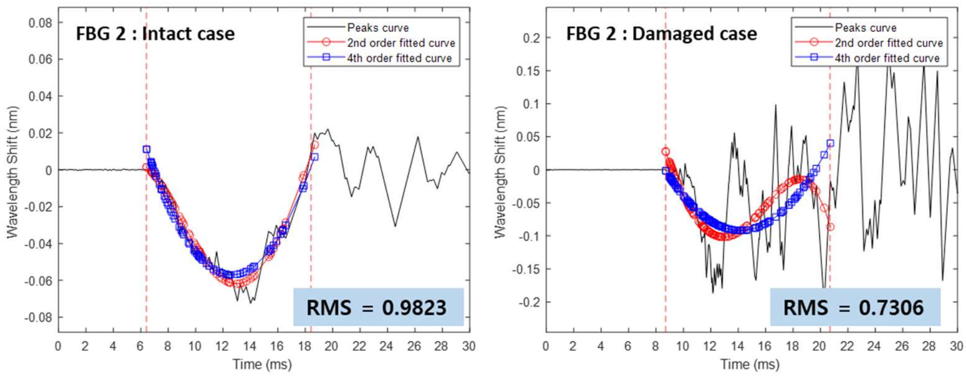

Figure 6. Impact signals and fitted curves of FBG sensor 2.

CONCLUSION

In this study, a real-time damage detection method was proposed for in-situ monitoring of low-velocity impacts on the composite structures. This method uses the impact signals obtained by an FBG sensor which is immune to electromagnetic interference (EMI). Also, this measurement system is quite simple, making it highly applicable to real structures. This suggested method was validated through the experimental results about the full scale composite wing box structure. In the experiments for validations, four multiplexed FBG sensor array was adopted to simultaneoulsy capture impact induced signals on the larger test section.

In order to estimate the delamination area for checking the severity of the damage, damage evaluation method was also attempted to develop. This method uses the number of path lengths between adjacent peaks which are shorter than the threshold value. Such short path lengths are induced by acoustic emissions from damage occurrences. As the damage caused by the impact increases, the number of short path lengths increases. In this study, the possibility of this hypothesis was verified using the result data of the experiments about various laminate specimens.

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