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Abstract
In the case of composite structures, low-velocity impact events can cause various types of damage that are mostly hidden inside the laminates or occur on the side opposite to the impact. Thus, damage cannot be easily detected by visual inspection or conventional NDT techniques. Moreover, if the damage occurs between the scheduled inspection periods, the possibilities of extensive damage or catastrophic failure can be increased. For these reasons, built-in NDT systems, such as the real-time impact monitoring system, are required in most composite structures for high reliability and ease of maintenance. In this paper, such an impact monitoring system, including impact location detection and damage assessment techniques, was studied for composite flat and stiffened panels. In order to acquire the impact-induced acoustic signals, four multiplexed fiber Bragg gratings (FBGs) and commercial high-speed FBG interrogator were used. In signal processing for the detection of impact locations and damage occurrences, neural networks and wavelet transforms were adopted. Finally, these algorithms were embodied using MATLAB and LabVIEW software to obtain a user-friendly interface.

Keywords
Impact location detection, impact damage occurrence, composite structures, fiber Bragg grating sensor

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1. Introduction

Today, composite materials are widely applied to aerospace structures and various types of vehicles because they have advantages for reducing structural weight and manufacturing cost thanks to their specific strength and stiffness, which are higher than those of metals. However, composite materials exhibit anisotropy in physical and thermal properties [1], so that their mechanical behavior and fracture characteristics can be more complex. Moreover, there are variations in mechanical properties for different fabrication methods. Thus, in order to completely replace metals by composites as primary materials, it is indispensable to enhance their reliability and safety.

Especially, composite materials show weakness against low-velocity impact events due to their low interlaminar shear and transverse tensile strength. Also, such impact damage (delamination, debonding) is hard to detect by conventional NDT methods. Although some advanced NDT methods can detect such damage, much time and cost can be required because the methods should be applied to all suspect regions. In order to overcome these vulnerable points, impact monitoring techniques using built-in sensor networks have been suggested. To monitor impact events, fiber optic and piezoelectric sensors have been widely used to acquire impact-induced signals. Further, various signal processing methods for impact identification, and damage assessment have been studied in previous researches. However, the sensor systems used in previous researches [2–11] have some limitations, such as limited covering area and low applicability to real structures due to high cost and complexity.

In this paper, we propose an impact monitoring method including detection of impact locations and damage occurrences in composite structures using a multiplexed, high speed fiber Bragg grating sensor system. For impact monitoring, sensor systems have to detect high-frequency signals over tens of kHz from impact events. However, previously, in order to acquire high-frequency signals in multiplexed fiber optic sensors, there were many difficulties in terms of complex system construction, high cost, etc. The FBG sensor system (SFI-710, Fiberpro Inc., Korea) used in this paper is capable of simultaneously detecting impact signals over 4 points [12]. However, the sampling frequency of this system is relatively lower than that of other sensor systems. Thus, to adopt this interrogator into an impact monitoring system, appropriate signal processing methods are suggested and verified through impact and fracture experiments. As a result, compared to the results of other current research, we demonstrate a more applicable and efficient impact monitoring technique based on a fiber optic sensing system.

2. Detection of Impact Locations

2.1. Impact Experiments

Detection of impact locations is a type of nonlinear inverse problem because one must estimate the impact location using impact-induced sensor signals without

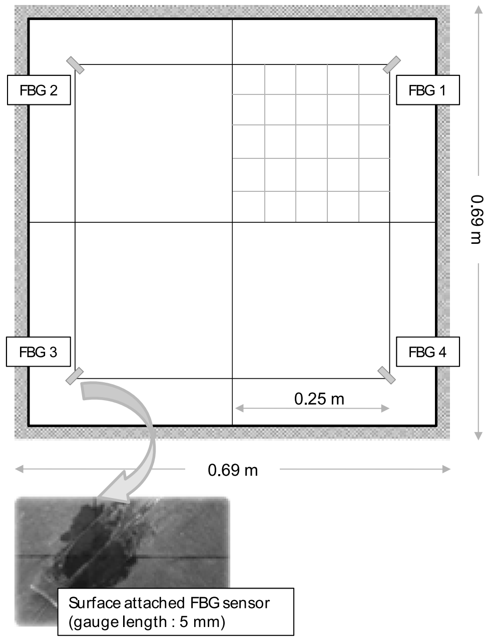


Figure 1. Composite flat plate specimen. This figure is published in color in the online version.

advance information about impact position. Especially, composite materials are composed of fiber and matrix so that the triangulation method using each impact signal's speed causes large errors [3] or demands numerous sensors and complex systems [4, 5]. Although some researchers have applied the neural network algorithm to overcome these limitations, most have used piezoelectric sensors to cover a large area of composite structures [6]. Piezoelectric sensors are easily interfered with by electro-magnetic environments and have many demerits, such as bulky sensor cables and high-cost measurement equipment. Thus, in order to increase the applicability of an impact monitoring technique to real structures, a fiber optic system is more appropriate.

Figure 1 shows the composite flat plate specimen for the impact experiment. The stacking sequence is $[45/90/-45/0_2/-45/0/90/0/-45/0/45/90/-45/0]_s$ and the thickness is 4.7 mm. Figure 2 shows the composite stiffened panel specimen as one part of a real composite wing structure. This specimen has six stringers, and the stacking sequence is $[\pm 45/0/45/90/-45]_s$. As depicted in Figs 1 and 2, four multiplexed FBG sensors with a grating length of 5 mm were attached on the inner surface of each specimen.

Impacts were given for each grid point on the specimens and the impact energy level was 1.0 J in order to prevent impact-induced damage. The impactor has a hemispherical tip with a diameter of 10 mm and its weight is 1.46 kg. For the composite flat plate, impact experiments were carried out only in the 1st quadrant region because the plate is a quasi-isotropic structure. On the other hand, impact

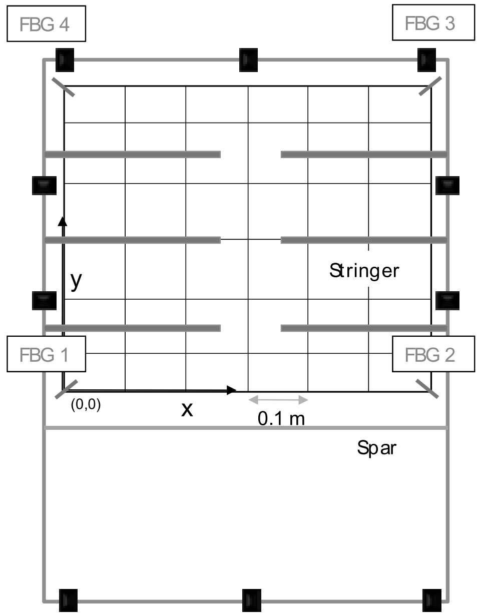


Figure 2. Composite stiffened panel specimen. This figure is published in color in the online version.

experiments were performed in the whole region for the composite stiffened panel. Then, the FBG sensor signals were collected at a sampling frequency of 40 kHz.

2.2. Neural Network Training

The neural network is composed of many calculating elements imitating the human nervous system and is widely used for nonlinear modeling, pattern recognitions and complex decision making problems. Just like a neuron in the human nervous system, each node in the neural network exchanges information and there are weights that show association levels between each node. These weights are determined by training, using the input-output patterns for convergence to target values with an allowable error. In this study, the arrival time differences in pair of sensor signals and the corresponding locations on the x- and y-axes were used as input and output data respectively.

Figure 3 shows the FBG sensor signals at the (0.2, 0.15) point in the composite stiffened panel specimen. As shown in Fig. 3, the FBG sensor system in this study was able to capture the impact events properly. In order to obtain the arrival time of the FBG sensor signal, the detailed portion D_2 was employed from the wavelet transform of the original sensor signal because this portion of each signal has similar frequency regions for all FBG sensors. Then, the moment in which the signal level is over one-and-a-half times the noise level is determined as the arrival time. Using these obtained arrival times of each FBG sensor, the input data for the neural network were calculated as $t_{12} = t_2 - t_1$, $t_{23} = t_3 - t_2$ and $t_{34} = t_4 - t_3$.

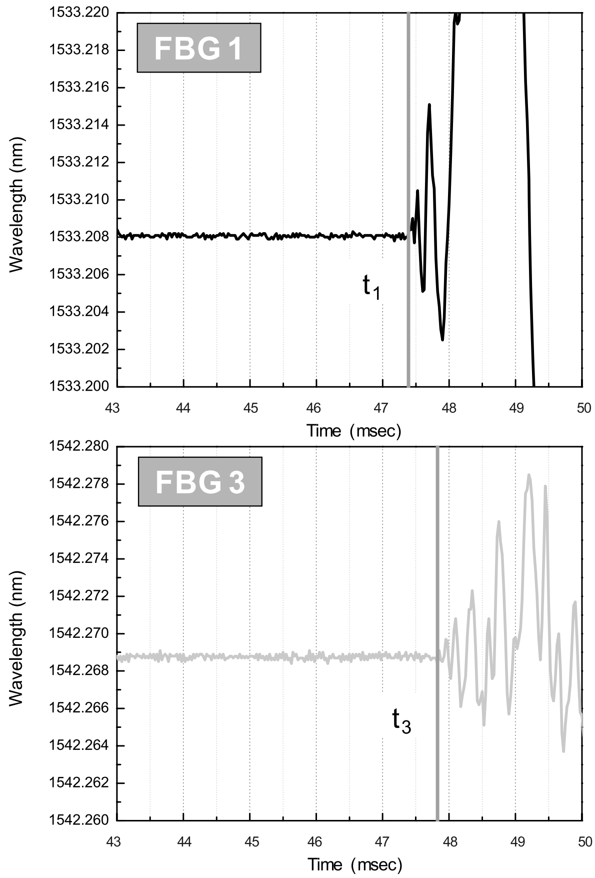


Figure 3. Impact signals of FBG sensors 1 and 3 in the composite stiffened panel. This figure is published in color in the online version.

2.3. Results of Impact Location Detections

After the neural network trainings using the input–output patterns from the impact experiments on the composite flat and stiffened panels, the results for the impact location detections were determined and are shown in Figs 4 and 5. In the case of the composite flat plate, the average error was 8.20 mm and the maximum error was 24.62 mm. For the composite stiffened panel, the average and maximum errors were 11.85 and 48.72 mm, respectively. From these results, the detected locations can be seen to be sufficiently distinguished because the resultant errors are smaller than the grid size. Moreover, this study used the minimum number of sensors for a relatively large covering area. Therefore, the results of this study are quite meaningful compared with those of other researchers in terms of applicability, system cost and complexity.

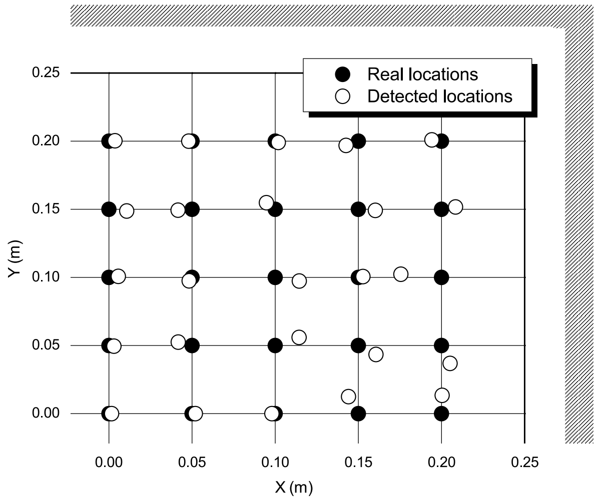


Figure 4. Detected impact locations for the composite flat plate.

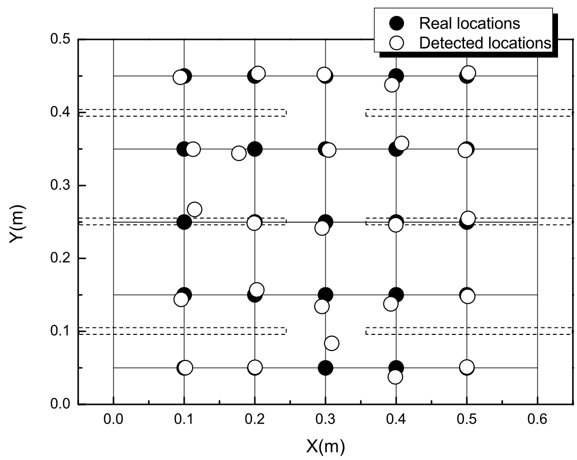


Figure 5. Detected impact locations for the composite stiffened panel.

3. Detection of Damage Occurrence

3.1. Local Fracture Experiments

When impact events occur in less important regions of composite structures, the information about detected locations is available for efficient inspections on the ground. However, if high energy impacts that can incur any damage happen in critical parts of structures, it is important for users to be notified whether impacts have occurred or not during operation. Thus, research into the detection of impact damage occurrences in composite structures was attempted in this study.

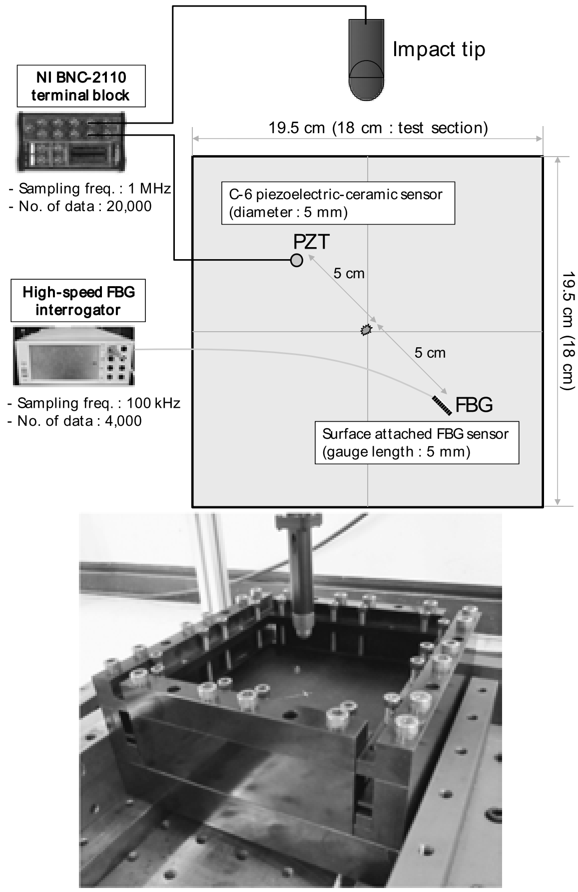


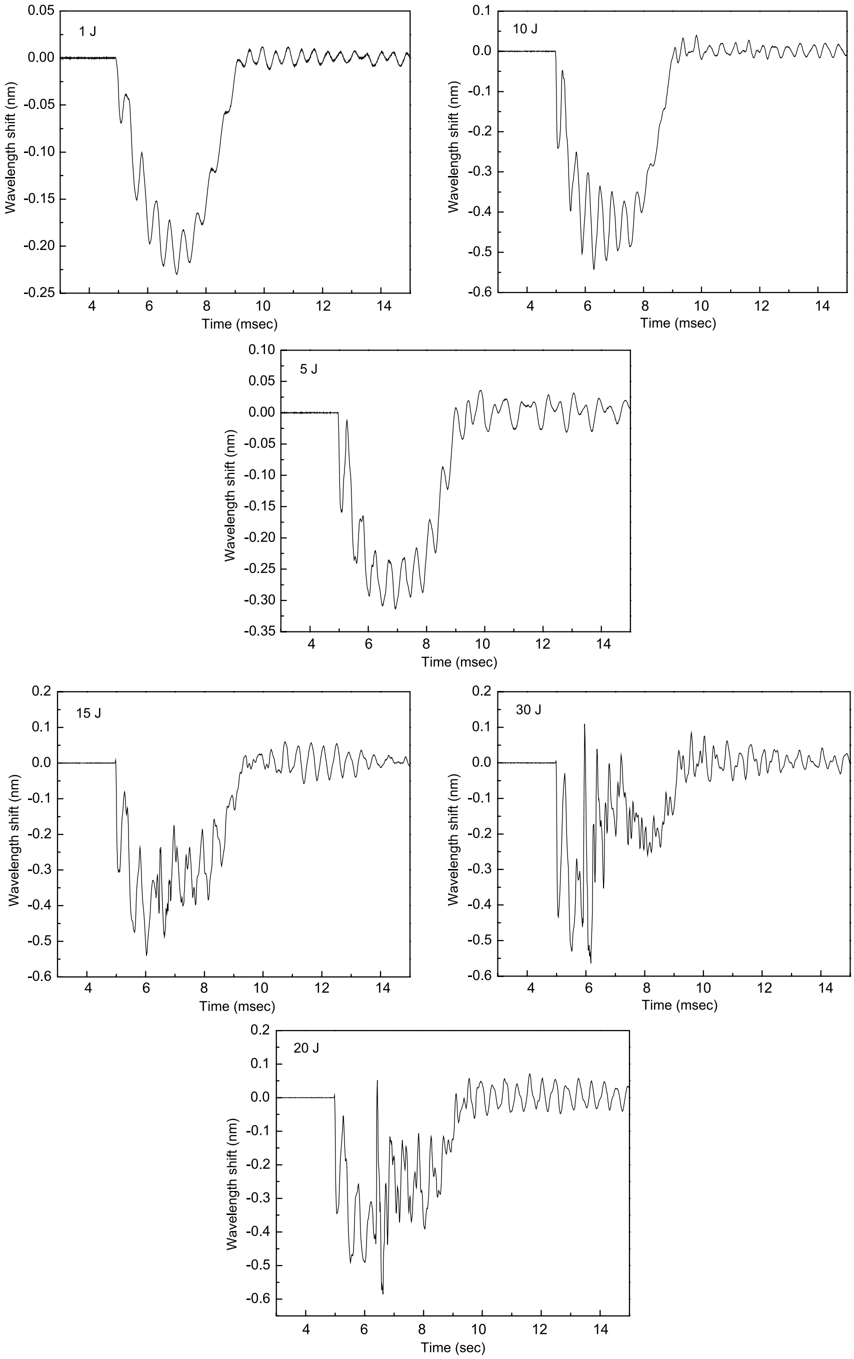
Figure 6. Impact damage detection experimental setup. This figure is published in color in the online version.

The specimens for local fracture experiments are the same as the composite flat plates in the impact experiments. The experimental setup is shown in Fig. 6 and the FBG sensor signals were measured in a sampling frequency of 100 kHz. The impact energies were 1, 5, 10, 15, 20 and 30 J for each specimen. Two specimens were tested for each impact energy.

Impact damage levels were evaluated by C-scan method because these levels cannot be detected by visual inspections. As a result, delaminations with a diameter of 30 mm were found in the specimens that had impact energies over 15 J.

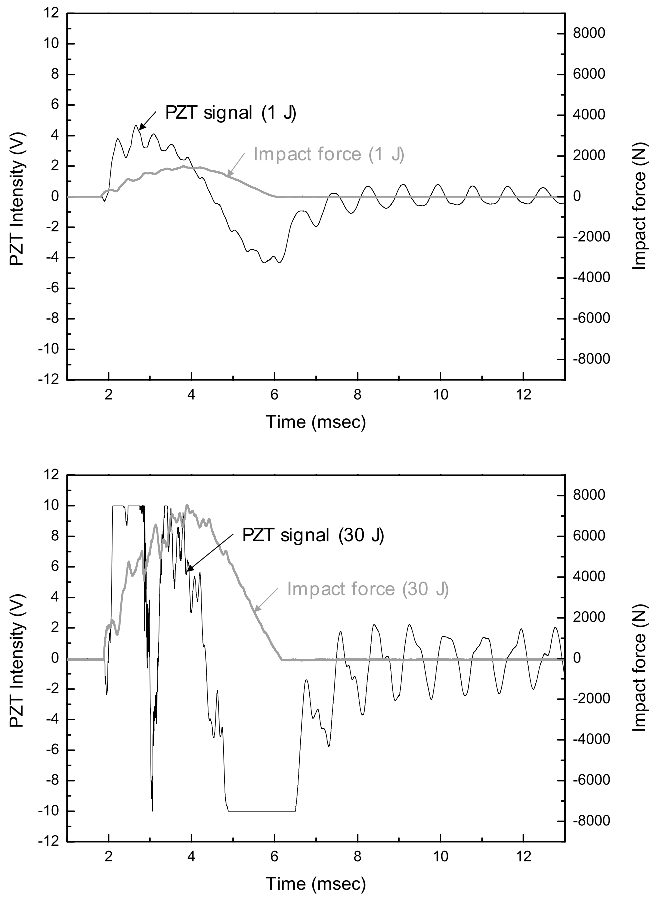
3.2. Damage Occurrence Detection

The FBG sensor signals obtained from local fracture experiments are shown in Fig. 7(a). In the FBG sensor signals for intact cases (1–10 J), it can be seen that vibration signals due to impact events were loaded in low-frequency signals by deflections of the structure. Although the amplitudes gradually increased with impact



(a)

Figure 7. Sensor signals from fracture experiments: (a) FBG sensor signals, (b) PZT sensor signals and impact force histories. This figure is published in color in the online version.

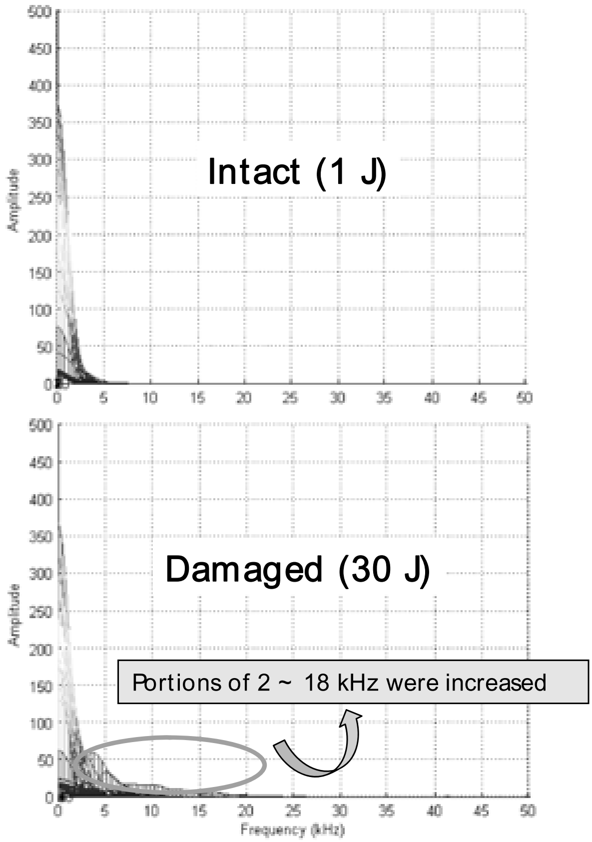


(b)

Figure 7. (Continued.)

energy, there was no evidence of damage occurrences. However, the characteristics of the FBG signals were different in the cases of damage (15–30 J). In these signals, there were high-frequency acoustic emission (AE) signals and suddenly changed in frequency portions due to fracture events. In order to check these characteristics, the force histories and PZT sensor signals in the cases of 1 and 30 J are shown in Fig. 7(b). There were also high-frequency AE components and sudden changes in the PZT signals. For a more detailed frequency analysis, short-time Fourier transforms (STFT) were applied to the FBG and PZT signals. As shown in Fig. 8(a), the frequency portions in the range from 2 to 18 kHz were found in all damaged cases regardless of impact energy. Although the frequency bandwidth was different, some specific frequency portions due to the fracture were also found in the STFT results of PZT signals.

Even if doubt remains about the insufficient sampling frequency of the sensing system in this study, it is clear that the frequency band related to fractures could

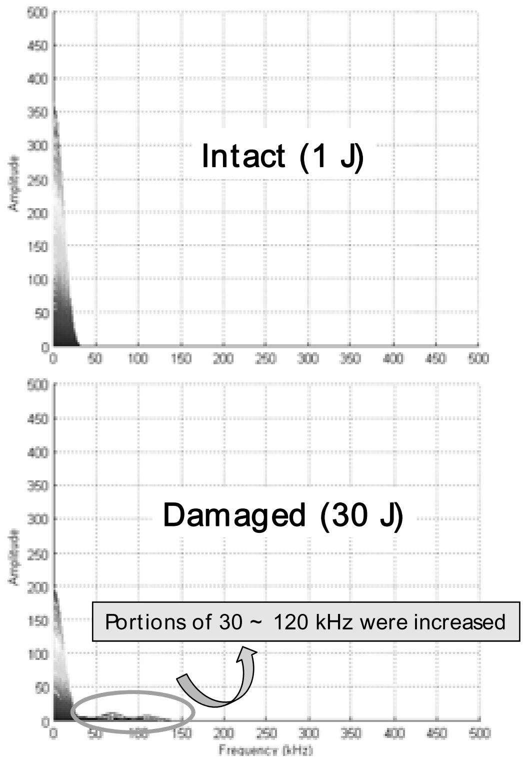


(a)

Figure 8. STFT results of sensor signals from intact and damaged cases: (a) TFT results of FBG signals, (b) STFT results of PZT signals. This figure is published in color in the online version.

be detected. However, the STFT was not adequate as a damage detection method because it can lead to faulty information due to users' subjective determination; the method also required long data processing time. Thus, quantitative approaches that can extract the related frequency portions and calculate their amounts were needed for objective evaluation. Among the possible signal processing methods, the wavelet transform (WT) method was adopted in this study. In previous research [7], the sharing portions of the detailed wavelet components (D_1–D_4) were used as criteria for decisions about damage occurrence. However, this method is applicable to cases in which a sufficiently high sampling frequency is used, but not to this limited system. In order to overcome these limits, the first task is to find the detailed wavelet components with frequency ranges from 2 to 18 kHz. The second task is to calculate the sharing portions for exact quantitative evaluations of damage occurrences.

Figure 9 shows the wavelet components of the intact and fractured signals up to decomposition level 4. The results of the frequency analysis for each wavelet



(b)

Figure 8. (Continued.)

component showed that D_2–D_3 have frequency portions related to damage and components beyond D_4 have frequency portions lower than 2 kHz (D_1: 32 ~ 42 kHz, D_2: 10 ~ 18 kHz, D_3: 5 ~ 12 kHz and D_4: 1 ~ 8 kHz). Moreover, the amounts of low frequency components (beyond D_4) accounted for almost 90% in the obtained sensor signal. In other words, it is hard to detect meaningful frequency components due to their relatively low proportions. The calculated result of sharing portions in overall time was shown in Fig. 10(a). Thus, for effective detection of such frequency components, quantitative evaluation in the vicinity of the fracture moments (2.5 ms from the arrival time) has to be performed. Figure 10(b) shows the results of calculating the sharing portions of detailed wavelet components (D_1–D_4) with the above method.

As shown in Fig. 10, the sharing portions of D_2–D_4 were distinguished according to damage occurrences without regard to impact energies. This result was consistent with the STFT results, which show that D_2 and D_3 increased due to damage occurrences. Furthermore, the increasing amount of these frequency portions was almost similar (20%) in all damaged cases, so that this value could be used as a criterion for damage occurrences. Thus, the results of this experiment show that the high-speed FBG interrogator with a limited sampling frequency was capable

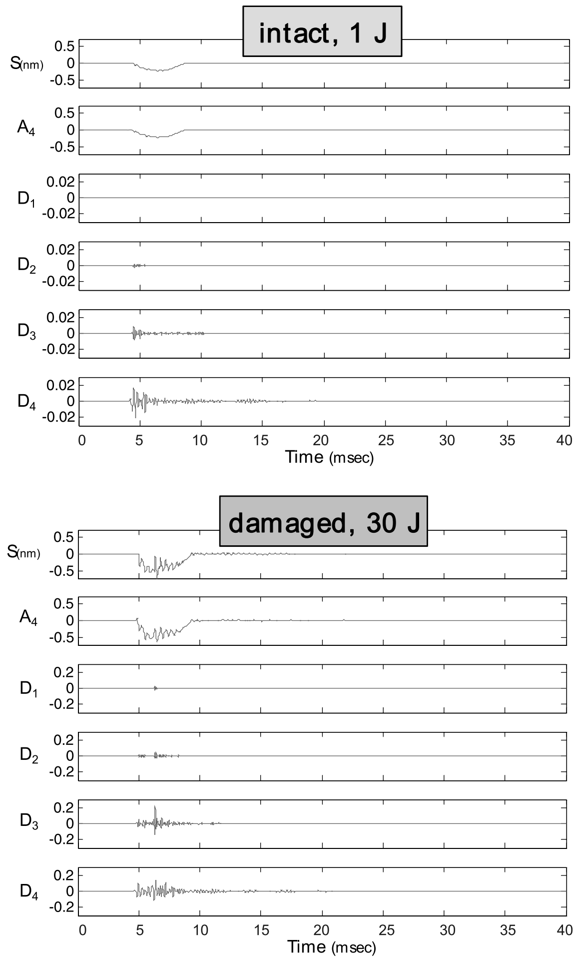
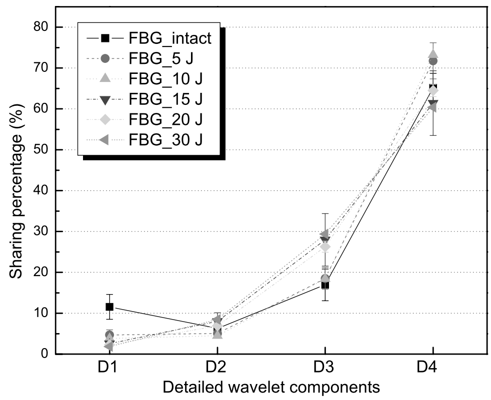


Figure 9. Wavelet decomposed components of intact and damaged signals. This figure is published in color in the online version.

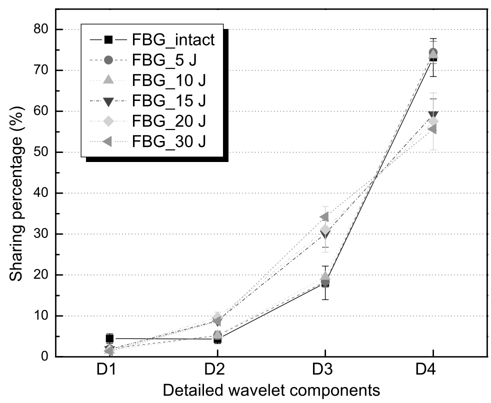
of detecting damage occurrences in composite structures. Although currently the suggested algorithm using this interrogator could not distinguish various types of damage, it was able to offer useful information about early stage structural health conditions of multiple types of damage.

3.3. *Effects of Angles between Sensors and Impacts*

FBG sensors have different sensitivities according to the direction of the sensor axis. Thus, in order to apply FBG sensors to real structures, the effects of sensor direction on the suggested algorithm have to be verified. To check these effects on the damage occurrence detection algorithm, FBG sensors with different sensing directions to impact point (0, 45, 90°) were attached to the bottom side of a composite flat plate specimen, as shown in Fig. 11. Then, an impact of 15 J was applied to the center



(a)



(b)

Figure 10. Sharing portions of detailed wavelet components from the suggested method: (a) sharing portions of detailed wavelet components in overall time, (b) sharing portions of detailed wavelet components in event time. This figure is published in color in the online version.

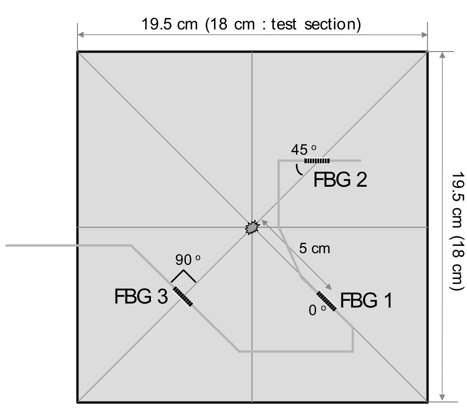


Figure 11. Experimental setup for effects of impact angles. This figure is published in color in the online version.

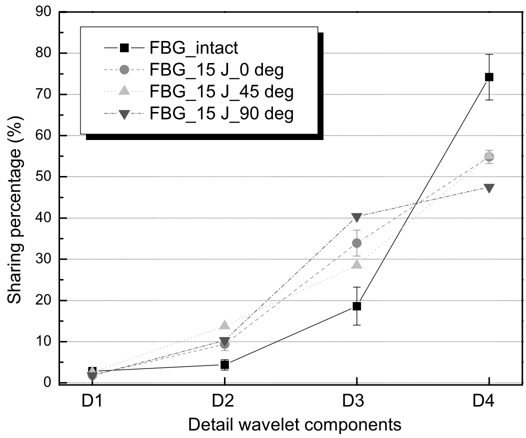


Figure 12. Sharing portions of detailed wavelet components for different impact angles. This figure is published in color in the online version.

of the specimen to induce fractures. Figure 12 shows the sharing portions of the detailed wavelet components for each FBG sensor signal with different directions. This result shows that the FBG sensor with a direction of 90°, though having the lowest sensitivity, can offer similar changes of damage related frequency portions for damage occurrence detections. Moreover, this experiment is meaningful for real applications because the results show the possibility of impact damage detection using multiplexed FBG sensors.

3.4. Effects of Different Sampling Frequencies

In this study, different sampling frequencies were used for the detection of impact locations (40 kHz) and damage occurrences (100 kHz). Thus, for simultaneous detection of impact locations and damage occurrences in real applications, characteristics of sensor signals due to different sampling frequencies have to be examined. Figure 13 shows the FBG sensor signals with different sampling frequencies due to an impact on (0.5, 0.25) points in the composite stiffened panel specimen.

As shown in Fig. 13, each wave form in the different sampling frequencies was similar and each leading wave arrived at the FBG sensor at almost the same time. Thus, the suggested algorithm for impact location detection using 40 kHz signals can be applied to 100 kHz signals without difficulty. In other words, information for impact locations and damage occurrences can be obtained from the FBG sensor signals sampled at 100 kHz in the covering area of the structures.

4. Conclusions

In this study, a more applicable impact monitoring technique was suggested and verified for composite aero-vehicle structures. In order to acquire high frequency signals due to impact events, a commercial high-speed FBG interrogation system

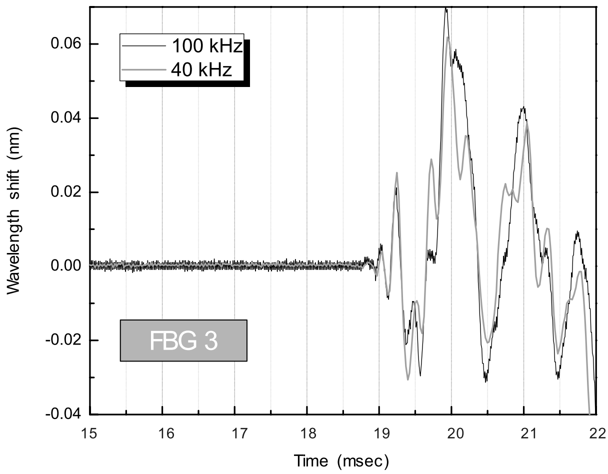


Figure 13. FBG signals of different sampling frequencies. This figure is published in color in the online version.

was adopted. With high performance and efficiency in terms of multiplexing in the high frequency band, this system can contribute earlier adoptions of impact monitoring techniques to real composite structures. Previously, however, the development of appropriate algorithms for impact monitoring was required because the sampling frequency was lower than that of other systems in previous research.

As a first step, impact identification was performed for composite flat and stiffened panel specimens with large covering areas. Compared to the results of previous research, we can show the detection of impact damage in a larger covering area and real complex test articles using a simple and low cost system. Next, the damage occurrence detection method was suggested using the fracture signals obtained by the FBG sensors. From these local fracture experiments, it was found that the quantitative evaluation of damage occurrences was possible using STFT and WT. Moreover, through the studies of the effects of FBG sensor directivity and different sampling frequencies on the suggested algorithms, we are able to propose simultaneous applications for detecting impact locations and damage occurrences. For the reasons mentioned above, the impact monitoring algorithms suggested in this study are feasible for application to real composite structures in the near future.

Acknowledgements

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