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광센서에 의한 탄소섬유/에폭시 복합재료의 파괴신호 측정 및 파괴기구에 관한 연구

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In-situ Monitoring of Failure and Fracture Mechanisms in Carbon Fiber/Epoxy Composite by an Optical Fiber Sensor

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요 약 : Multimode 광섬유 센서를 이용하여 탄소섬유/에폭시 복합재료가 파괴될 때 방출되는 음향방출신호를 검출하였고 이 신호의 주파수 특성을 분석하였다. 검출된 음향방출신호는 4개의 구간으로 구분할 수 있는데, 이 구간들은 에폭시 매트릭스에서의 균열발생 및 에폭시와 탄소섬유 경계에서의 결합분리, 탄소섬유의 파괴, 그리고 새로운 위치에서의 에폭시의 균열 등의 복합재료의 파괴기구와 일치함을 알았다. 따라서 본 연구에서 사용한 multimode 광섬유는 복합재료의 파괴특성을 비롯한 제반 특성의 비파괴시험에 이용될 수 있으며, 특히 비파괴적인 In-situ 시험에 적합한 방법이라고 믿어진다.

Abstract : Acoustic emission signal generated by the fracture of carbon fiber/epoxy composite laminates has been detected by an internally embedded multimode optical fiber sensor. The observed acoustic emission signal is then frequency-analyzed via FFT. It was found that the four characteristic regions representing those of the four-step fracture mechanism of long fiber-reinforced composites could be successfully identified by measuring frequency signatures. Therefore, a multimode optical fiber can be utilized as a sensor for an in-situ monitoring of the characteristics of fiber-reinforced composites under fracture process.

INTRODUCTION

Physical properties of carbon fiber/epoxy composites have been extensively studied because of its usefulness as a major structural material. Of many physical properties, the fracture behavior of fiber-reinforced composites may be one of the important properties that needs to be thoroughly understood. The reason for this is that the fracture of composite is directly related to the safety of the human-being who uses the structures made of such composites.

Many nondestructive methods have been proposed in studying the fracture behavior as well as failure behavior of composite materials.[1] One of the very recent nondestructive methods is the one which employs a multimode optical fiber as a sensor for an analysis of composite's characteristics.[2] An optical fiber was developed originally for a long distance transmission of signals because of such advantages as low loss in transmitting signal and a low disturbance of signal by external factors. Recently, optical fibers have been utilized as a sensor to measure such physical quantities as electromagnetic wave, ultrasonic wave, pressure, or temperature.[3~7] Optical fiber sensors are more advantageous in measuring the properties of composites than conventional ultrasonic sensors in the sense that (1) they can be directly embedded inside the fiber-reinforced composite so that the continuous in-situ monitoring of composite's characteristics is possible and (2) a full length of optical fibers can act as a sensor so that it can be used for the specimen of a large area. In these senses, an optical fiber is one of the most promising candidates for monitoring characteristics of large scale fiber-reinforced composites.

In this study, therefore, as an effort to explore the applicability of optical fiber sensors, the acoustic signal generated by the failure of carbon/epoxy composite was detected by a multimode optical fiber sensor which is embedded inside the composite. Also, detected signals were analyzed in conjuction with the fracture mechanisms of carbon fiber/epoxy composites.

EXPERIMENTALS

Prepregs used throughout the experiment were fabricated by passing the long carbon fibers through a solvent-epoxy bath and subsequent drying the solvent. Acetone was used as a solvent to reduce the viscosity of epoxy and thus to improve the surface coatability of epoxy. NMA(Nadic Methyl Anhydride) and BDMA(Benzyl Dimethyl Amine) were used as a hardner and an initiator for curing the laminates, respectively. Carbon fibers were PAN series T-800 of Toray Inc., Japan, the properties of which can be seen in Table 1. The epoxy was a bisphenol-type YD-128 details of which are shown in Table 2.

A single multimode optical fiber was placed in the middle of 6 prepregs in parallel to the direction of the carbon fiber alignment. Such prepared laminate was compression molded at 150℃ for 3 hours under the pressure of 6 tons following a 30 minute preheating at 100℃ and cooled under the same pressure. Thus prepared composite was 6.5 cm long and 1.0 cm wide. The diameters of core and cladding of the optical fiber used in the pre-

Table 1. Properties of Carbon Fiber

Type	Filaments	Tensile Strength (kgf/mm^2)	Tensile Modulus (kgf/mm^2)	Elongation (%)	Density (g/cm^3)
T-800*	12,000	570	30,000	1.9	1.80

* Product of Toray Ind., Japan.

Table 2. Properties of Epoxy

Type	epoxy equivalence	Viscosity (cp), 25℃	Molecular Weight	Specific Gravity
YD-128*	185-190	11,500-13,500	370-390	1.17

* Product of Kukdo Chemical Co., Korea.

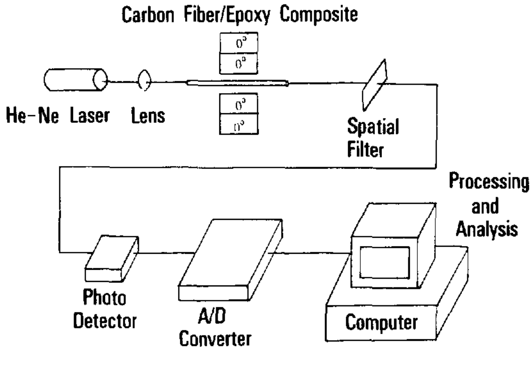

Fig. 1. Schematic representation of measurement setup.

sent study were 50 μm and 125 μm, respectively.

An instrumentation used in the present study is shown in Fig. 1. First, an optical fiber embedded carbon fiber/epoxy composite was fixed in a grip designed not to disturb the path of travelling light through the optical fiber. Then, the light of 633 nm wavelength from a He−Ne Laser was continuously passed through the embedded optical fiber and the output signal was continuously detected while the force was applied gradually along the direction perpendicular to that of the carbon fiber alignment. The output signal was detected by a pin-diode light detector after a spatial filter. Then detected electrical signals were recorded and analysed by a personal computer with the data aquisition system.

Throughout the present study, the force applied to break the composite was not recorded because the main purpose of this study was to detect the acoustic emission signal coming from the failure of composite and correlate the detected signal with the fracture mechanisms of the fiber-reinforced composite.

RESULTS AND DISCUSSION

Typical Output Signal

While the force is applied to the carbon fiber/epoxy composite, many small fluctuations in output signal from the pin-diode detector were observed, the typical one of which is shown in Fig. 2. In this figure, X-axis represents the time in seconds and Y-axis represents the attenuation in output signal.

The acoustic emission generated during the fracture of the composites propagates through the composite layers, and it causes a local fluctuation of the alignment of optical fiber sensor. This perturbation acts as a simulator to change the conditions for the total reflectance of the travelling light inside the optical fiber. The net result is that the intensity variation at the end of the optical fiber is directly related to the change of pressure affecting the optical fiber.[4,5]

At a glance at Fig. 2, one can see that the output

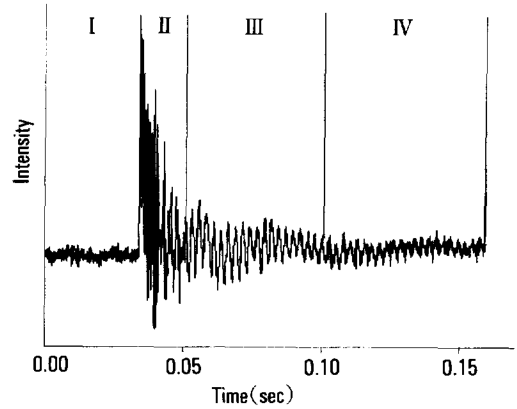

Fig. 2. A typical acoustic emission signal obtained by an optical fiber sensor when fracturing carbon fiber/epoxy composite.

signal can be divided into four regions each of which shows a different frequency characteristic. These were assigned as Region I, II, III, and IV in order of increasing time. The signal in Region I can be characterized as a stationary state always with a small amplitude. Right after this, there was always a sudden and intensive fluctuation in an output signal(Region II) followed by a gradual transition period(Region III). Finally, another stationary state but with a wave characteristic(Region IV) was again observed at the end of the gradual transition period.

Analysis of Detected Signal

One of the ways to analyze the time-domain data is to obtain the frequency characteristics, so that in this analysis the time-domain result was converted into the frequency-domain one using a so-called Fast Fourier Transformation(FFT) technique. Such analysis can provide the information on the frequency characteristic for each region.

The frequency characteristics for four regions of detected acoustic emission signal are shown in Fig. 3. In this figure, 3-(a), (b), (c), and (d) represent the frequency characteristics for Region I, II, III and IV, respectively. As shown in Fig. 3, each region has characteristic peaks at various frequencies those of which were summarized in Table 3. These characteristic frequencies were determined

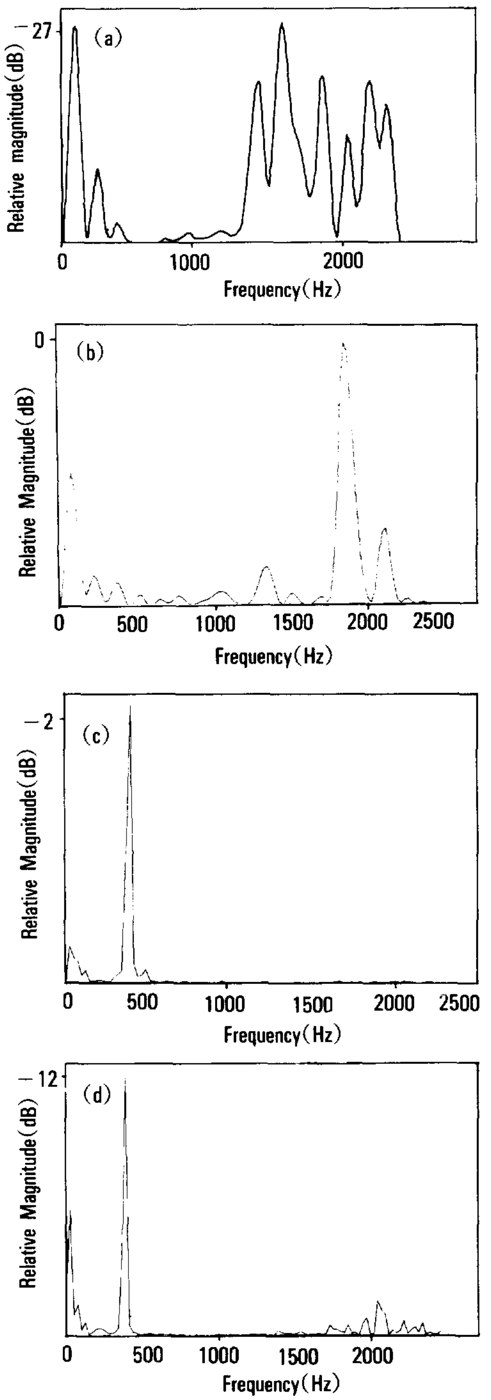

Fig. 3. Frequency characteristics for Region I, II, III, and IV in Fig. 2 : (a) Region I, (b) Region II, (c) Region III, and (d) Region IV.

Table 3. Peak Frequencies for Region I, II, III, and IV

Region	Frequency(Hz)
I	80*, 1900
II	80, 1900*
III	400*
IV	60*, 400

* Characteristic frequencies for corresponding regions.

after a careful comparison of many other observed peaks for each region. In particular, as shown in Fig. 3-(a), Region I has many peaks in a frequency range of up to 2500 Hz, but the peak at about 80 Hz is distinguishable and spurious peaks are distributed over the range from 1400 Hz to 2500 Hz. In Region II shown in Fig. 3-(b) two main peaks at about 80 and 1900 Hz were observed. On the other hand, Region III shown in Fig. 3-(c) has one main peak at about 400 Hz and Region IV shown in Fig. 3-(d) two peaks at about 60 and 400 Hz.

The interpretation of characteristic frequencies representing each region is not simple because most regions have two peaks in a frequency domain, as shown in Table 3. However, a careful comparison of the magnitude of peaks indicates that the peak heights are different depending on the region where they appear. In Region I, a peak appears at 80 Hz and distributed peaks can be found over the frequency range from 1400 Hz to 2500 Hz resembling random signal behavior. Whereas, in Region II, the peak at 1900 Hz is quite dominant, compared to the one at 80 Hz. Therefore, 80 Hz is the characteristic frequency for Region I and 1900 Hz that for Region II. On the other hand, it is obvious that the characteristic frequencv for Region III is 400 Hz because it has only one distinct peak. Then it can be said that 60 Hz is the characteristic frequency for Region IV. These are summarized in Table 3.

The fact that multiple peaks, or two peaks in many cases, were observed for a region indicates that the characteristic frequencies are overlapped because of the following two possibilities : One possibility is in the technique to differentiate the regions. Here, as mentioned earlier, four regions were differentiated just by their appearance, i. e., stationary state, sharp increase in output signal, a gradual transition period, and another stationary state. A more careful differentiation of each region may exclude the overlapping of characteristic frequencies. The other is due to the physical phenomenon that more than a distinct step of composite failure process occur concurrently over a region, especially near the areas between two regions.

Interpretation in Conjuction with Fracture Mechanisms

As mentioned earlier, the failure of composite structures emits an acoustic signal which in turn affects the alignment of embedded optical fibers and consequently the detected acoustic emission signal is believed to originate from the failure of carbon fiber/epoxy composites. On this basis, it will be adequate to interprete the observed results in conjunction with the failure or fracture mechanisms of carbon fiber/epoxy composites.

The fracture mechanisms of fiber-reinforced composites have been investigated by many investigators. Regarding this, four-step fracture mechanism is the most widely known one.[8~10] Briefly speaking, cracking of the matrix materials and debonding of carbon fibers from the matrix are the first step for the fracture of composites. The next step is the fracture of carbon fibers. The third one is the so-called pull-out phenomenon where the acoustic signal is generated by a friction of the pull-out carbon fibers. Finally, cracking of the matrix materials and debonding of carbon fibers from the matrix will start at nearby spots. All these processes create the acoustic signals with different amplitudes and different frequencies which are of our concern in this study.

Coincidently or not, the acoustic emission signal obtained in the present study was divided into four characteristic regions and, as mentioned earlier, the frequency characteristics are distinguishable depending on the region. To confirm the detected signal is closely related to the fracture mechanisms of fiber-reinforced composites, two simple experiments were carried out : One experiment was to break the composite with the embedded optical fiber parallel to the direction of the alignment of carbon fibers (the longitudinal fracture). This experiment may simulate the situation where the cracking of the matrix and debonding of carbon fibers from the matrix can occur without an extensive fracture of many carbon fibers. Fig.4 shows the experimental result, where (a) is the detected output signal in a time domain and (b) is the frequency characterteristic in a frequency domain. As shown in Fig. 4-(b), one peak at about 90 Hz was obtained so that it can be said, combined with the result shown in the Fig. 3-(a) and 3-(d), that the peaks at this frequency range are the characteristic peaks for the matrix cracking and debonding mechanism. The other experiment was to break a bundle of carbon fibers. For this experiment, a bundle of carbon fibers were broken in front of the microphone connected to the acoustic signal collector, the result of which is shown in Fig. 5. In the figure, (a) shows a wave-like response in a time domain and (b) shows the frequency characteristics obtained via the FFT. From this figure, combined with Fig. 3-(b), one can see that the peak at about 2000 Hz is a characteristic peak for the fracture of carbon fiber only.

Unfortunately, however, the acoustic emission signal from the pull-out process could not be obtained because of the difficulties in experimentation. Also, the exact frequencies at which the peak maxima in a frequency domain appear are little different depending on the situation. In case of the matrix cracking and fiber debonding mechanism, for example, the characteristic frequencies are 80 Hz for Region I, 60 Hz for Region IV and 90 Hz for the longitudinal fracture. A similar feature was observed in the case of fracture of carbon fibers. 1900 Hz was the characteristic frequency for Region II whereas 2000 Hz was that for the fracture of a single carbon fiber in front of the microphone. The observation of different frequencies may not be surprising because the situations under which

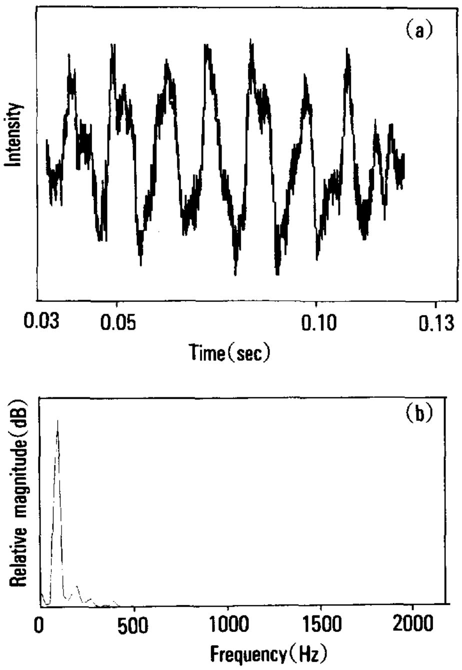

Fig. 4. Acoustic signal and frequency characteristic from a longitudinal fracture : (a) Acoustic signal in a time domain and (b) Spectrum of (a).

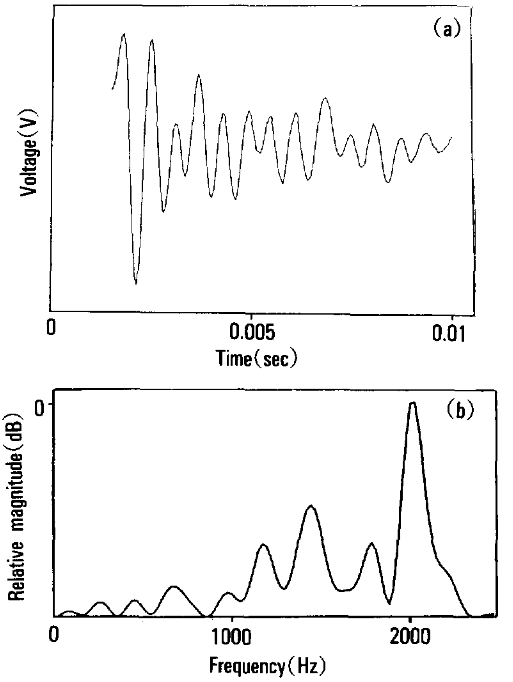

Fig. 5. Acoustic signal and frequency characteristic from a fracture of a bundle of carbon fibers acquired by a microphone : (a) Acoustic signal in a time domain and (b) Spectrum of (a).

the specimen was tested were slightly different. Regarding the matrix cracking and fiber debonding mechanism, the acoustic emission from the matrix cracking and fiber debonding at fresh spots should be different from that at spots near the previously failed region, possibly stronger at the fresher spots. Also, the fracture of carbon fibers in a free space(fracture in front of microphone) may be different compared to that in a restricted area (within the composites). An implication is that the harder the materials are the higher Hz the characteristic frequencies are resulted in. It is, anyhow, necessary to investigate the relationships between the composite characteristics and peak positions in a frequency domain.

Nevertheless, the above experiments suggest strongly that the acoustic emission signal detected in the present measurement system is directly related to the fracture mechanisms of carbon fiber/epoxy composites. Along with the results from two simple experiments, four regions shown in Fig. 3 can be distinguished as follows even though the respective processes may happen overlapped to a certain degree : Region I as the matrix cracking and debonding process, Region II as the fracture of carbon fibers, Region III as the pull-out process, and finally Region IV as the matrix cracking and fiber debonding at nearby spots.

CONCLUSIONS

Acoustic signal generated by the fracture of carbon fiber/epoxy composite laminates has been successfully detected by an internally embedded multimode optical fiber sensor and the detected acosutic signal was analyzed using a FFT technique. The major conclusions are as follows :

(1) The observed acoustic signal is composed of 4 characteristic regions each of which has the dif-

ferent frequency characteristic. These are assigned as Region I, II, III, and IV, representing those of the four-step fracture mechanism of long fiber-reinforced composites.

(2) Four characteristic regions represent the four-step fracture mechanism of long fiber-reinforced composites. Region I having a characterictic frequency of 80 Hz was assigned as the matrix cracking and fiber debonding at fresh spots, Region II having a characteristic frequency of 1900 Hz as the fracture of carbon fibers, Region III having a characteristic frequency of 400 Hz as the pull-out of fractured carbon fibers, and Region IV having a characteristic frequency of 60 Hz as the matrix cracking and fiber debonding at nearby spots.

(3) Therefore, a multimode optical fiber can be utilized as a sensor for an in-situ monitoring of the characteristics of fiber-reinforced composites under the fracture process.

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