Study of damage evaluation method using frequency change in the tensile test of CFRP

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Abstract

We have been studying the damage evaluation method during the tensile test of Carbon Fiber Reinforced Plastic (CFRP) materials by Acoustic Emission (AE) method. We reported previously that there were some possibilities to detect a sign of delamination occurred by the variation of Frequency Center of Gravity (F.C.O.G). F.C.O.G became high with increasing stress. On the other hand, it was also confirmed that the F.C.O.G became low when damage has occurred. Theses results, we investigated the reason that the F.C.O.G changed by damage.

We conducted the hammering test and the fiber bundle tensile test. The frequency affected by the vibration characteristics of CFRP became high with increasing stress until specimen broke. Then we confirmed that the F.C.O.G with another low frequency component was generated after the occurrence of matrix cracks. In the result of fiber bundle test, the source of this low frequency component was the carbon fiber.

1. Introduction

CFRP has been increasingly used as several engineering fields. Composite overwrapped pressure vessels are used for aerospace and automotive applications for the purpose of weight reduction. In the aerospace field, AE testing was considered as integrity evaluation of the composite pressure vessels during proof tests [1] and several standards for the evaluation that ASME has been already established [2]. It was generally used for the Felicity Ratio (FR) as one of ASME standard [3][4][5]. The FR was a way of measuring the level of damage put into a structure. To calculate the FR, it was necessary to detect the load which AE signal started and to determine the ratio of the previous load. Therefore, it was not able to detect each generated damages such as micro crack, matrix crack, delamination and fiber breakage. In order to detect these damages, it is necessary to analyze the characteristics of the AE signals.

In the static stress, they were characterized from shape of AE signal’s waveforms by other researchers [6]. On the other hand, in the dynamic stress, researched using AE parameters such as peak amplitude, duration of waveform, integrated value of amplitude and count [7][8][9]. The damage mode of AE was classified by the time-frequency which was obtained by dividing the count in duration [10]. Recent years, the frequency analysis had become possible because waveforms of AE signals were able to almost record by the evaluation of hardware. Therefore, various analysis methods were reported [11][12].

We have studied F.C.O.G. This method can detect just before delamination occurs [13]. Then we confirmed the effectiveness of this method for CFRP pressure vessel [14]. However, it was not confirmed why F.C.O.G. changed at each generated damages.

We expected that the vibration characteristic was changed by CFRP stretches due to stress loading. Therefore, we investigated the vibration characteristic of CFRP at each stress. Then, in order to detect only AE signals from fiber, we expected tensile test using specimen which was made from fiber bundle.

2. AE testing by tensile test

2.1. Experimental Method

We considered the AE testing by tensile test of CFRP. The test specimen was made in accordance with ISO 527-4. It is the standard condition for isotropic and orthotropic fiber-reinforced plastic composite. The CFRP specimen was manufactured by laminating Torayca prepreg P3252S of which fiber was T700SC. This laminated configuration was [0/45/90/-45] 4S. Specimen size was 250 mm in length, 25 mm in width and 3 mm in thickness as shown in Figure 1. The CFRP tabs with 50 mm in length attached at the both ends of the specimen. In this test, we used two AE sensors which were set directly on the specimen.

The stress was increased in a staircase pattern until the specimen was broken as shown in Figure 2. The vertical axis is tensile stress and the horizontal axis is measurement time. Tensile stress was applied at the four cycles loading at 0 to 238 MPa, 0 to 476 MPa, 0 to 714 MPa and 0 to 825 MPa which was the broken stress. AE signals were detected with the two AE sensors during the tensile test.
2.2. Results of AE testing by tensile test

AE hits during the tensile test are shown in Figure 3. The horizontal axis is tensile stress, and the vertical axis is hits / MPa. Hit is number of the detected AE signals. FR is generally used for damage evaluation in AE testing. FR is the load where considerable AE resumes, divided by the maximum applied load. FR was calculating by the each loading. The AE signals mostly were not detected until the previous maximum stress before the 3rd loading in Figure 3. These FRs were approximately 1.0. In the 4th loading, FR was reduced 0.84. The passing criterion was higher than 0.95 from ASME code X article TR 6. Then, it was considered that the damage of the specimen occurred during the 3rd loading.

In order to characterize the each AE signal, we calculated the F.C.O.G by using Equation (1). Results of the calculations are shown in Figure 4. The horizontal axis shows applied stress and vertical axis shows F.C.O.G. The unit of the F.C.O.G is kHz. The color shows the number of AE signals by the range of 5 MPa divided by the 2 kHz.

The white diamonds are the most concentrated part of the F.C.O.G at each 20 MPa.

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F.C.O.G = \frac{\sum_i (A(f_i) \times f_i)}{\sum_i A(f_i)} \quad (1)
\]

In the applied stress lower than 420 MPa, the concentrated parts of F.C.O.G became from 80 kHz to 100 kHz with increasing load. However when the stress was from 420 MPa to 700 MPa, concentrated parts became low until 80 kHz. In the applied stress higher than 700 MPa, F.C.O.G concentrated in 70 kHz until the specimen was broken. The FR began to decrease during the 2nd to the 3rd loading. Therefore, it was considered that the FR was decreased with the lower F.C.O.G. Moreover, if the F.C.O.G of detected AE signals was almost 70 kHz, FR was less than the passing criteria from ASME code. From these results, the frequencies of detected AE signals changed with increased loading in 60 kHz to 140 kHz.

We reported that the results of the cross-sectional observation at the tensile stress of 293 MPa and 666 MPa [15]. From the results, during the concentrated part of F.C.O.G was high, damage to the specimen was Micro Cracks. Then, in the stress where the F.C.O.G was low, Matrix Cracks generated in the specimen and the FR decreased. When the F.C.O.G reached the lower limit, delamination generated. Concentrated part of the F.C.O.G continuously changed with the tensile stress.
3. Investigated Vibration Characteristic

3.1. Experimental Method

From the results of chapter 2, we assumed that the frequencies of generated AE signal were changed by the specimen stretched in tensile stress. Therefore, we thought that it was necessary to investigate the vibration characteristics of the CFRP in the loading stress. The test specimen had the same shape as the chapter 2 as shown in Figure 5. Impulse hammer was used to provide excitation. The vibrations were measured by the accelerating sensor. The increasing step of the tensile stress was 80 MPa. At each stress step, the hammering test was performed while holding load as shown in Figure 6. The two installed AE sensors detected the AE signal generated when the stress was increased.

3.2. Results of Hammering test

The waveforms of the hammering test show the Figure 7. The measurement waveform at 0 MPa shows (a), (b) is 400MPa and (c) is 720 MPa which is just before broken. In the waveform of (a), the vibration damped and the waveform showed free vibration. The arrow part in the figure was considered to be the primary mode of the natural frequency of the bending vibration.

Compare the waveforms (a), (b) and (c), as load stress increased, it seemed that the duration of waveforms were shortened and frequencies were higher.

![Figure 5: Tensile specimen](image)

![Figure 6: Hammering Test](image)

![Figure 7: Waveforms of the hammering tests](image)
Then we confirmed that the frequency of the AE signals which generated during the increasing load. Figure 8 (b) shows the results of the FFT of AE signals. The horizontal axis shows the applied stress, the vertical axis shows frequency and the color shows amplitude of frequency spectrum. The color amplitudes show the average value of each 10 MPa.

From the results of chapter 2, the generated damages were able to assume at the each loading stress. The matrix cracks generated at the stress higher than 420 MPa. In the tensile stress lower than 200 MPa, the high amplitude generated at frequency from 60 kHz to 140 kHz.

At the stresses higher than 420 MPa, the frequency of the high amplitude part increased to 200 kHz. At a stress of 800 MPa just before broken, the frequency was further increased to 300 kHz. Then the frequency of the high amplitude part was able to confirm in the 50 kHz, at the stress higher than 420 MPa. Matrix cracks occurred from this stress. In these results, although frequency bands were different, the results of the hammering tests and the frequency of AE signals were showed the same tendency.

The natural frequency of CFRP was considered that the frequency increased as the specimen stretched with tensile stress. Therefore, the low frequency generated after the occurrence of matrix cracks was considered as vibration on the carbon fiber or resin.

4. Frequency investigation of AE signals generated from carbon fiber

4.1. Experimental method

In order to confirm the low frequency of AE signal generated by the occurrence of matrix cracks, we investigated the frequency of AE signals generated from only carbon fiber.

The carbon fiber bundle was applied to the specimen. The part of the specimen was hardened with resin.

The parts hardened with resin were 105 mm from the both ends of the specimen shown in Figure 9. The hardened part was CFRP. Specimen was prepared that the thickness of the CFRP part was 3mm. The carbon fiber and the resin were used the same material of prepreg of the Torayca P3252S.

The two GFRP tabs were set the 75 mm part from the both ends. The chuck parts of tensile test machine were 50 mm. AE sensors were installed at the part of hardened by resin and the GFRP tabs.

The AE signals generated by the carbon fiber were propagated through the resin and arrived to AE sensors. This propagation pass was the same as the CFRP tensile test.

The load was increased constantly until broken. In this test, we took the pictures of the fiber breakage using a high-speed camera.
4.2. Test Results

Figure 10 (a) shows the time history of tensile load. The horizontal axis shows test time and the vertical axis shows the tensile load. The value of the tensile load shows the percentage of the broken load. Figure 10 (b) shows the FFT of the AE signals. The horizontal axis shows the test time, vertical axis shows the frequency and the color shows the amplitude of frequency spectrum. The color amplitudes show the average value of each 10 MPa.

The load was applied to the specimen for test time of 100 seconds. Till the load was lower than 20% at the test time of 300 seconds, almost AE was not detected. The low frequency of 50 kHz generated between 350 to 500 seconds at the load was 20% to 80%. This was the same frequency as the low frequency of AE confirmed in chapter 3.

Pictures taken with a high-speed camera are shown in Figure 11. When the specimen was installed on the testing machine, the carbon fiber was slacked as shown in Figure 11 (a). At the test time of 100 seconds, the carbon fiber became straight and the load was started to apply as shown in Figure 11(b). The several carbon fibers were broken at the edge after the amplitude of the frequency decreased as shown in Figure 11(c) at the test time of 516 seconds. Fiber breakage that can be confirmed in the picture occurred in only 2 seconds during 584 seconds to 586 seconds as shown in Figure 11 (d) and (e).

Therefore, the source of 50 kHz frequency component was not AE caused by the fiber breakage. Further investigation is needed on the source of this low frequency AE.
5. Conclusions

In this study, we investigated the reason that the F.C.O.G changed by damage. In the hammering test, the primary mode of the natural frequency became high with increasing load until specimen broke. Another frequency component generated after occurrence of matrix cracks. The frequency of AE during CFRP tensile test was same tendency although frequency range was different. In the results of the fiber bundle test, we confirmed that this low frequency component was the AE by generated from CFRP. Therefore, F.C.O.G becoming low was thought that the low frequency components from the CFRP generated due to the occurrence of matrix cracks.

However, although the cause of frequency change could be assumed, the frequency range was significantly different between hammering test and actual AE signals. Assuming that the frequencies of AE signals were high order natural frequency, it was necessary to study using theoretical formulas and FEM analysis. In addition, we schedule to investigate further the low frequency generated from the carbon fiber.

References


