INTEGRITY EVALUATION OF COPVS BY MEANS OF ACOUSTIC EMISSION TESTING

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Abstract

It is important to evaluate the integrity of composite overwrapped pressure vessels (COPVs) used for space applications. In order to examine applicability of acoustic emission testing (AT) for the evaluation, AE signals were monitored during the pressurization test of a COPV before and after an impact test. The impact test of 17-J energy was conducted by using a drop-weight impact tester to simulate machine-tool drop. A large number of emissions were monitored by the AE channel nearest the impact point. In addition, the characteristics of AE signals detected nearest the impact point were different from those by other channels. From these results, it is assumed that AT can be used for the qualitative integrity evaluation of COPVs. On the other hand, to realize the quantitative integrity evaluation, it is essential to make database of AE parameters.

Introduction

Composite overwrapped pressure vessels (COPVs) are widely used for space applications, such as accumulators for a space satellite and propellant tanks for a rocket. It is known that COPVs are likely to suffer complicated internal damages by being dropped or by impacts of dropped machine-tools. Even when such internal damages occurred, only small damages are caused on the impact surface in many cases. Therefore, it is difficult to find the impact damages from outer surface by visual testing (VT). Since the internal damages may reduce strength of the vessels, a reliable nondestructive testing (NDT) for the damages is desired. Applicability of various NDT methods for COPVs was evaluated by several investigators [1-3], although, the optimal inspection technique is not yet found.

Acoustic emission testing (AT) is one of the candidates for the NDT method of COPVs. Several standards on AT, such as ASME section V, article 11 [4] for evaluating the integrity of fiber-reinforced plastic vessels are available. Only a few papers [5-7] or reports [8], however, appeared in public domain for applying AT to COPVs.

In our previous study [9], the applicability of AT to the integrity evaluation of COPVs was evaluated by using coupon-level specimens. It was found that Kaiser effect and Felicity effect observed during a cyclic loading test can be used for evaluating previously induced damages such as impact damages. The detectable minimum damage size by AT was same or better than that by ultrasonic testing (UT).
In this study, as a collaborative research between Tokyo Institute of Technology and Japan Aerospace Exploration Agency, AE monitoring is conducted during the pressurization test of a real COPV before and after the impact test. IHI Inspection & Instrumentation Co., Ltd. joined this study in the measurement under the guidance of Tokyo Institute of Technology. Suitable AE parameters for the integrity evaluation are investigated and the applicability of AT is evaluated.

**Experimental Setup and Procedure**

A thin metal-lined composite overwrapped spherical pressure vessel of 600-mm diameter was prepared for this study. Reinforcement fibers of the vessel were carbon fibers. The vessel was fabricated by filament-winding (FW) method. Prior to this study, the vessel was pressurized to MEOP (maximum expected operating pressure) 52 times, proof pressure (1.25MEOP) 6 times and nominal burst pressure (1.5MEOP) once. Thus, it is assumed that several damages were already inflicted on the COPV before the start of this study.

Four AE sensors (Vallen-Systeme GmbH, Type VS150-RIC, nominal resonant frequency 150 kHz) were mounted on the outer surface of the vessel at quadrant locations on the equator (see Fig. 1). The programmed hydrostatic pressure cycles were applied to the vessel. The maximum pressure was set as the MEOP and was held for 30 minutes. Outputs of the AE sensors were amplified 34 dB by preamplifiers and filtered by band-pass filters of 95 to 850 kHz. The extracted signals were digitized at an interval of 200 ns with 4096 points by A/D converter.

After the first pressurization test, an impact test was conducted with a drop-weight impact tester. A hemispherical tip of 12.7-mm in diameter was used for the impactor per ISO14623. Before the impact test, AE sensors were removed from the vessel to avoid sensor damages. The impactor was dropped to the vessel along guide rails and the impact load was applied at the position 22.5° from the Ch.-4 sensor on the equator of the vessel as shown in Fig. 1. The weight of the impactor and the impact energy were 2.5 kg and 17 J, respectively. The surface damage caused by the impact was not evident by VT. After the impact test, the damage evaluation was conducted by using an ultrasonic flaw detector and UT located an elliptically shaped internal damage of about 40 mm in long axis and about 20 mm in short axis. Following the impact test, AE sensors were remounted on the same positions as before. AE activities were again monitored during the pressurization test by the same programmed pressure cycles.

Fig. 1 Schematic representation of the pressurization test and the sensor positions.
Results and Discussion

Figure 2 shows the total number of AE hits for each channel during the pressurization test before and after the impact test. Before the impact test, the total number was almost identical among each channel. After the impact test, the total number of Ch. 4, which was the nearest to the impact point was more than twice those by other three channels. The result shows that by comparing the total number of AE hits by each channel, previously induced damages such as impact damages can be evaluated.

Fig. 2 The total number of AE hits for each channel during the pressurization test, before and after the impact test.

Figure 3 shows peak amplitude of AE signal (left) and cumulative AE hits (right) with the elapsed time. The normalized pressure history is overlapped with these graphs. Periods A-D defined in the right are used later in detailed analysis. A large number of significant AE signals
(>65dB) were monitored by all channels throughout the first pressurization test, which was conducted before the impact test (see upper left of Fig. 3). The result reveals that the large damages occurred all over the vessel at the first pressurization test. During the pressure-hold periods of the first (before impact) and the second (after impact) pressurization tests, emissions were continuously detected. Since emissions that continue during pressure-hold generally indicate structurally significant defects, the COPV appears to have significant defects from the beginning as we mentioned in the previous section. By monitoring the AE peak amplitude and the cumulative AE hits, a newly induced damage and a damage progression can be monitored. In addition, there is a possibility to evaluate the existence of significant defects by monitoring AE during the pressure-hold.

Figure 4 shows the relationship between AE signal peak amplitudes and durations. In general, an AE event with high amplitude and long duration reveals the occurrence or progression of large-scale damage. Since a large number of such kinds of events were detected during the first pressurization test, large-scale damages or progressions occurred during the first test.

![Fig. 4 Relationship between AE signal peak amplitude and duration.](image)

![Fig. 5 Relationship between cumulative AE hits and AE peak amplitude.](image)
Fig. 6 Relationship between cumulative AE hits and AE peak amplitude of Period A to D for AE signals detected before the impact test. (Periods A to D are defined in right of Fig. 3.)

Fig. 7 Relationship between cumulative AE hits and AE peak amplitude of Periods A to D for AE signals detected after the impact test.
Figure 5 shows the relationship between cumulative AE hits and AE peak amplitude in dB before and after the impact test. The scale of the vertical axis is logarithmic. When a fracture mode is limited to one, cumulative AE hits in the graph tends to be monotonically decreased with increasing the amplitude. Therefore, the relationship of Ch. 1 to 3 monitored during the second pressurization test after impact (right of Fig. 5) reveals that fractures with limited fracture-mode occurred. On the other hand, the relationship monitored during the first pressurization test before impact (left) and Ch. 4 of the second test reveals that fractures with several fracture-modes occurred. Since there was a possibility that the fracture-modes change with elapsed time, we investigated the transition of the relationship with the elapsed time. Figure 6 and 7 show the results. As strong non-linear relationship was observed for the first pressurization test, we had assumed the relationship changed with the elapsed time. However, as shown in Fig. 6, the relationship was almost the same throughout the pressurization test. Therefore, it can be stated that fractures with several fracture-modes occurred throughout the first pressurization test. On the other hand, as shown in Fig. 7, the relationship of Ch. 4 changed with the elapsed time and quite different from those of Ch. 1 to 3 at periods A and B. This reveals that AE related to the impact damage occurred from early stage (periods A and B) of the pressurization test.

![Fig. 8  Centroid frequency of detected AE signals with respect to the elapsed time. The normalized pressure history is superimposed on the graphs.](image)

Figure 8 shows the centroid frequency of detected AE signals with the elapsed time. The distributions of the first test (before impact) and the second test (after impact) appear to be different from each other. In order to examine details of the distributions, centroid frequency’s histograms for each channel were investigated. The results are shown in Fig. 9. While AE signals below 400 kHz are dominant for the first test (before impact), AE signals above 400 kHz are observed for the second test (after impact). It is assumed that the origins of AE signals are different for first and second tests. It is also important that in the second test, AE signals with high frequency components (above 500 kHz) are frequently detected by Ch. 4, which is located closest to the impact point. AE signals, which are related to impact damage are likely to generate high-frequency components. Since there was a possibility that the distributions change with elapsed time, we investigated the transition of the histogram with the elapsed time. Figure 10 to 13 show histogram of centroid frequency of periods A to D.
Fig. 9  Centroid frequency histograms for each channel.

Fig. 10  Centroid frequency histograms for each channel in period A.
Fig. 11 Centroid frequency histograms for each channel in period B.

Fig. 12 Centroid frequency histograms for each channel in period C.
Distributions of the histogram for the first test are almost identical. This indicates that the origins of the AE sources did not change with the elapsed time. On the other hand, distributions for Ch. 4 of the second test changed with the elapsed time. It is also noted that the distributions are quite different from those of other channels at periods A and B and also different from those of Ch. 1 to 3 at periods A and B. This reveals that AE related to the impact damage occurred from early stages (periods A and B) and this AE consists of high-frequency components.

Fig. 13  Centroid frequency histograms for each channel in period D.

Figures 14 and 15 show the relationship between cumulative AE hits and load histories before and after the impact test. All AE hits were plotted in Fig. 14, while AE hits with above 40 dB peak amplitude were plotted in Fig. 15. If a perfect Kaiser effect is established, cumulative AE hits should monotonically increase with the load. As shown in the upper plot of Fig. 14, perfect Kaiser effect was not observed even during the first pressurization test, which was conducted before the impact test. This is due to the vessel may have prior internal damages from earlier testing. Felicity effect was clearly observed for both the first and the second tests (indicated by arrows). Contrary to Fig. 14, almost perfect Kaiser effects were observed below 30% of the MEOP in Fig. 15. This result indicates that the adequate threshold should be set for an appropriate damage evaluation. Focusing on Ch. 4 data of Figs. 14 and 15, Felicity ratio seems reduced after the impact test. This indicates that the damage severity of COPVs can be evaluated qualitatively by Felicity ratio.

In the first part of this paper, we found that AE signals related to impact damage were observed at early stages (periods A and B) and involved high-frequency components (from Figs. 10 and 11) with low peak amplitude (from upper plot of Fig. 7). On the other hand, in the last
part of the paper, we found that Felicity effects are observed clearly when the AE signals with small peak amplitude are eliminated. These results indicate that the effect of the impact damage appeared throughout the experiment, although adequate AE parameters should be extracted for observing the effect of the impact damage. When the quantitative evaluation is needed, it is essential to make database of AE parameters and select appropriate ranges.

Fig. 14 Relationship between cumulative AE hits and normalized pressure. (Upper: The first pressurization test before the impact test. Lower: The second test after the impact test.)

**Conclusion**

In this study, the applicability of AT to the integrity evaluation of COPVs was evaluated. To simulate machine-tool drop, the impact of 17-J energy was applied to the vessel by using drop-weight impact tester. The programmed cyclic load by hydrostatic pressure was applied to the vessel before and after the impact test and AE activities were monitored during the test. In the pressurization test after the impact, the channel nearest the impact point detected a large number of AE hits. In addition, characteristics of AE signals detected nearest the impact point were different from those by other channels. From these results, it is concluded that AT can qualitatively make the integrity evaluation of COPVs. On the other hand, to realize the quantitative integrity evaluation, it is essential to make the database of AE parameters.
Fig. 15 Relationship between cumulative AE hits above 40 dB of AE signal amplitude and normalized pressure. (Upper: The first pressurization test. Lower: The second test.)

References

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