Abstract

It is important to evaluate the integrity of composite overwrapped pressure vessels (COPVs) used for space applications. In this study, applicability of acoustic emission (AE) monitoring to the integrity evaluation of COPV materials was evaluated by using coupon-level specimens. It was found that by evaluating emissions during load-hold and relationship between AE signal peak amplitude and duration, damage occurrences during the test can be monitored. We also found that Kaiser effect and Felicity effect can be used for evaluating previously induced damages. Detectable minimum damage size for previously induced damage by AE method may be same or less than those by ultrasonic testing.

Keywords: COPVs, CFRP, Impact damage, Integrity evaluation

Introduction

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

Acoustic emission (AE) method is one of the candidates for the inspection method of COPVs. Several AE standards, such as ASME section V, article 11 [4], which can be used for evaluating integrity of COPVs are available. Several papers [5 - 10] related to this problem appeared from 1970’s, but further studies are needed for AE method to become a major NDT method for COPVs. For example, key-parameters to selecting the inspection method, like the minimum detectable damage size, are not yet defined with AE.

In this study, in order to verify the applicability of acoustic emission (AE) method for inspecting damages of COPV materials, coupon-level CFRP specimens with impact damages of various size are prepared. AE signals from previously induced damages (impact damages) and newly induced damages (or progression of previously induced damages) are monitored during cyclic-load testing of the specimens. Suitable AE parameters for integrity evaluation of CFRPs are investigated. Detectable minimum damage sizes are also discussed.

Specimen and Impact Test

A large-size plate of CFRP [0°/45°/90°/-45°]_{10} of 5.3 mm thickness was prepared by laminating pre-preg sheets. PAN-based carbon fibers of TR350 from Mitsubishi Rayon Co., Ltd. and
epoxy resin (hardening temperature: 150°C) are used for the sheets. Rectangular specimens with 150 mmL × 100 mmW were cut with the fiber directions (0°) on the top surface along the longitudinal direction.

Figure 1 shows a drop-weight test machine used for the impact test, which satisfied SACMA SRM 2R-94 standard. In this test, however, a hemispherical tip of 12.7-mm diameter was used based on ISO14623. The impactor (impact rod) was dropped along guide rails to the center of a specimen. The weight of the impactor was 1.57 kg. Edges of the specimen were clamped all around by steel flanges. Impact energy was 3, 7 or 10 J, controlled by the height of the impactor, Figure 2(a) shows an impacted specimen surface loaded at 10 J. Although it is the result of applying the largest energy (10 J) in this test series, surface damage is not easily locatable by visual testing. Figure 2(b) shows the cross-sectional profile of impacted surface along the dotted line in Fig. 2(a) by a surface profilometer. Maximum depth of the damage is less than 150 μm. The characteristics of shallow damage make it difficult to find. Damage will become less clear if the tip of impactor is blunter.

Figure 3 shows C-scan images of an impacted CFRP by ultrasonic immersion testing (sensor frequency: 5 MHz, scanning pitch: 0.3 mm). Circular shape internal damages are revealed for the specimen impacted at 10 J. Small damage is observed for the specimen impacted at 7 J and no
damage is observed for the specimen at 3 J. Considering that the surfaces of real COPVs are rougher than the test pieces and inspection of COPVs is conducted manually, detectable minimum damage size by ultrasonic testing (UT) in field may be that caused by 10 J-impact (Damage caused by 7 J-impact may be difficult to detect by field test.).

**Experimental Setup and Method**

After the impact test, both sides of the specimen were cut lengthwise into a 30-mm wide strip with the impacted position at center. Aluminum tabs were bonded to the end of each specimen for gripping. As shown in Fig. 4, an AE sensor of 150-kHz resonant frequency (Physical Acoustic Corp. (PAC): Type R15) was mounted on the surface of the specimen at the center along with two guard sensors (PAC: Type Pico, 500 kHz resonant frequency) (Fig. 4). Noise events generated outside of the specimen gage section were removed by these guard sensors. Outputs of the AE sensors were amplified 40 dB and digitized at an interval of 250 ns with 4096 points, and fed to a computer. AE analysis was conducted using VisualAE from Vallen Systeme GmbH.
Figure 5 shows the loading sequence of the experiment. Note that the loading/unloading rate is constant (±0.3 mm/min) for all cycles. At the load of 15, 30, 45, 60, 75 and 90 kN, crosshead was stopped and load was held. The load-hold period of each cycle was constant (3 minutes) for all cycles. Four specimens (sound specimen, specimen impacted at 3 J, 7 J and 10 J) were tested by this loading sequence.

**Result and Discussion**

During the tensile testing of the sound specimen and the specimen impacted at 3 J, new observable damages became visible on the surface at 82 and 72 kN (Fig. 6). On the other hand, no new observable damage was found for the specimens impacted at 7 and 10 J. Observable damages were not found for the latter specimens, although new invisible small damages or impact damage extension may have occurred above around 70 kN (Ultimate tensile load for these specimens is about 100 kN).

Figures 7 and 8 show AE signal peak amplitude and cumulative AE hits against elapsed time. The load history is overlapped with these graphs. During the load-holds at less than 60 kN, AE
activities were low. Hence, it is assumed that no macro damage or large damage progression occurred at these stages. On the other hand, when the load-hold value reaches at 75 or 90 kN, high AE activities were observed. These correspond to macro damage as shown in Fig. 6 and internal damage progression at these stages. The results show possibility to monitor damage occurrences (newly induced damages or extension of previously induced damages) during the pressurization test of COPVs by using these parameters. It is also noted that several AE signals were detected during the unload process for damaged specimens. This result coincides with that of Downs and Hamstad [9], who focused on AE signals during the unload process (They defined Shelby ratio, which is related to AE signals during the unload process, and used it for damage evaluations).
These unload AE signals are useful for evaluating the previously induced damages (such as impact damages). We will discuss these AE signals again along with the Felicity effect.

Figure 9 shows relationship between AE signal peak amplitude and duration. High amplitude and long duration emissions are detected with both the sound specimen and the specimen impacted at 3 J, from which observable large damages occurred. Therefore, it can be said that this relationship can be used for monitoring occurrences of large damages during the pressurization test of COPVs. A similar trend of emission is detected for the specimen impacted at 10 J, while
observable damages were not found. Invisible new damages or impact damage extension might have occurred in the specimen. On the other hand, no such emission is detected for 7J-impacted specimen. The size of new damage or damage extension might be small compared to those for other specimens.

Next, we examined the feasibility of AE method for detecting previously induced damages. Kaiser effect is the phenomenon that no AE activity is observed until the load reaches the level of the previous maximum load. When incomplete Kaiser effect is shown under cyclic loading, i.e. a considerable amount of AE is detected before the previous maximum load, the phenomenon is called Felicity effect. These effects have been used for evaluating integrity of composite vessels and piping. Figure 10 shows relationship between cumulative AE hits and load history. In Fig. 10(a), all AE data was used to draw the graph. In Fig. 10(b), only AE signals above 45 dB were used. If perfect Kaiser effect is established (i.e., no AE signals are observed during unloading, holding and loading below the previous maximum load), cumulative AE hits should increase.
Fig. 10 Relationship between cumulative AE hits and load: (a) AE signals with peak amplitude above 40 dB, (b) above 45 dB.
monotonically with load. As mentioned previously, new damage is expected occur above 70 kN. Since these new damages are considered to influence the evaluation of previously induced damages, the data above 70 kN were ignored (hatched part in the graph). Perfect Kaiser effect was observed when sound specimen was tested (surrounded by a dotted line in Fig. 10). On the other hand, when damaged specimens were tested, Felicity effect is observed (indicated by arrows). The Felicity effect is mainly caused by AE signals during unloading process as shown in Fig. 7. It is also noted that Felicity effect seems less influenced by threshold values (40 or 45 dB) in this range. These results indicate that AE method is a useful NDT method for evaluating previously induced small damage. Although database is limited, it appears that minimum detectable damage size by AE method is same or less than that by UT method.

Conclusion

In this study, we examined the applicability of AE method to the integrity evaluation of COPVs. We first prepared coupon level specimens and conducted impact test at various impact energy. We confirmed that impact damages were difficult to detect by visual testing. Furthermore, it was estimated that detectable minimum damage size by ultrasonic testing in field requires 10 J-impact for this test piece. AE monitoring was conducted during cyclic load testing of the specimens with various damage sizes. It was found that emissions during load-hold and relationship between AE signal peak amplitude and duration can be used for monitoring newly induced damages or progression of previously induced damages. On the other hand, Kaiser effect and Felicity effect can be used for evaluating previously induced damages. The results showed a possibility that detectable minimum damage size for previously induced damage by AE method is the same as or less than that by UT method.

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Reference