Damage evaluation for Type-II CNG cylinder
by the analysis of AE parameters

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Abstract
This research seeks to evaluate damage on the fuel tank by an acoustic emission test when executing 20000 cycles fatigue test and thereafter burst test. Used gas cylinders in the experimental are three types as follows; one is sound cylinder, others are cylinders which contain longitudinal and transverse artificial defect. when there was longitudinal defect, the location of burst was near the location of defect. This leads to the effect in which the thickness of the composite material becomes thinner according to the length of the longitudinal defect and this is judged to have an effect on the location of initiation and growth of crack in the liner. Also, for the acoustic emission signal, when there is longitudinal defect, the ratio of an event occurring at defect position among overall hits is more than 50 %, and the source location also accords very precisely with defect position.

Keywords: acoustic emission, fatigue damage, CNG cylinder, damage evaluation

1. Introduction

There are about 10 million vehicles run on natural gas in the world. There are about 1.7 million low-pressure LPG vehicles [1], and 17,000 high-pressure CNG vehicles running in Korea and the number is increasing.[2]

Generally for CNG vehicles, type II cylinder, where the increase in used pressure and lighter weight are achieved through fiber-reinforced composite material, which is wrapped in hoop-direction on the steel liner is used. Since 1984, the U.S. experienced more than 80 cases of vehicle fuel tank-related accidents [3] and Korea also experienced 8 cases in which the CNG tank exploded; thus, there is a need for the development of inspection technology for high-pressure fuel tanks. In the case of the U.S., the inspection technology of high-pressure fuel tanks were developed by DOD and NASA as an inspection technology for missile fuel tanks [4] but as the use of high-pressure fuel tanks for transport increased DOT executed a research on inspection technology for vehicles based on the research results of NASA and reported that among several NDT technology, Acoustic Emission (AE) has a possibility of being used as an inspection technology for vehicles [5,6]. The gas cylinder, which is made of fiber-reinforced composite material, is unlike cylinder made of only steel materials in that when the damage increases the acoustic generation activity increases but when the degree of damage increases even more, the acoustic generation activity rather decreases. [7]

So there is a need to secure an analysis of AE parameter and more databases in order to quantitatively analyze the degree of damage. [8]

In this paper, we realize the artificial defect in the wrapping composite material in the gas cylinder and go through fatigue test and AE test also burst test and execute a research on the effects of defect on the burst pressure and the possibility of extracting defects that can affect the life of the cylinder in the early stages.

2. Experimental Procedure

2.1. Experimental Cylinder

Experiment cylinder used in this research is a 64 Liter CNG fuel tank used in vehicles. The thickness of the liner in the shell is about 6 mm and was made using the DDI (Deep Drawing Ironing) method using 34CrMo4 steel plate, and is a type-II cylinder in which glass fiber is hoop-wrapped on the shell of the liner. Figure 1 shows schematic diagram of the experimental cylinder.
Table 1. Chemical composition of vessel liner (unit : wt.%)

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
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<tr>
<td>Max</td>
<td>0.38</td>
<td>1.00</td>
<td>0.40</td>
<td>0.015</td>
<td>0.010</td>
<td>1.20</td>
<td>0.40</td>
</tr>
<tr>
<td>Min</td>
<td>0.25</td>
<td>0.40</td>
<td>0.10</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

P+S ≤ 0.020

2.2 Method of experiment

Figure 2 shows schematic diagram of the experiment equipment for the acoustic emission test during the fatigue test of the cylinder.
As can be seen in the figure, pressure was put on the cylinder with a pump to control the pressure and acoustic emission signals were detected using acoustic emission sensors attached to the cylinder. And the signal were processed and analyzed after fed into AE equipment.

The fatigue test repeated 20000 cycles between 0 and 207 bar, afterwards which has a used pressure of 0 and afterwards, the pressure was continuously increased and the burst test was carried out. Figure 3 shows the conditions for pressurization.

![Figure 3. Load sequence during fatigue and fracture test](image)

The acoustic emission test acquired acoustic emission signals 3 times for 10 minutes in 207 bar in an interval of 4000 from 0~20000 cycles of fatigue test. The acoustic emission signal detected through the sensor attached to the composite material was put in the DiSP-52 Acoustic Emission workstation of PAC to analyze the signal.

The sensor was attached to the cylinder using jig and magnetic holder and in order to increase the transmission efficiency of the signal, vacuum grease was used as a couplant. In the AE test, R15I (PAC) sensor with the central frequency of 150 kHz was used and RG58A/U cable of 10 m in length was used. As a pressure medium, machine oil was used during the fatigue test and water was used for the final burst test. Simulated acoustic emission source for the sensitivity measure was a 2H pencil lead breakage of 0.5 mm in diameter and the sensitivity of the sensor was within 1 inch of the sensor with an average of 98 dB.

### 3. Results and Discussion

#### 3.1 AE parameters during fatigue test

Figure 4 shows AE parameters as the fatigue cycles increase in load holding stage. The fatigue gradually increases up to 8000 cycles and then increases even further from 12000 cycles before going down again. The rise time is known to have a correlation with the mechanism of acoustic emission signal source[9] and the acoustic emission signals appear to be generated by new mechanism around 8000 cycles.

In case of burst test, the damage mechanism for Type II vessel is known to be composed of creation and growth of crack, delaminating, fracture of fabric and abrupt fracture of metal vessel, etc[10]. However, in case of fatigue test, the matrix fracture was observed at about 20,000 cycles and then the crack increased as the number of fatigues increased showing the leak through the crack of matrix.

![Figure 4](image)
Figure 4. AE parameters with fatigue cycle for longitudinal defect cylinder:
a) Total hits, b) Average risetime, c) Average duration, d) Average amplitude

Figure 5 compares shows the event/hit ratio according to the increase in the number of cycle. This is a figure that shows the % of the number of hits that can precisely show the source among the total number of hits. In the case of longitudinal defect vessel, it was 41.8 % in the 4000th cycle, 55.7 % in the 8000th cycle. An event can be calculated using the difference in time that the resilience from the source (acoustic emission signal) sent through the walls of the vessel reaches the sensor and has to be extracted from at least 3 sensors. Hits that do not go by such standards cannot be used to calculate events and if the location was identified by simulation or if the signal is weak or is static, it cannot be recorded as an event. In the case of longitudinal defect vessel, the number of hits is small in the 4000th and 8000th cycle but the growth of the rupture is relatively easy and it sends hits to at least 3 sensors with signals with sufficient amplitude so the number of event/hit rate increases.

Figure 5. The ratio of events/ hits per sensor during fatigue test for artificial defect vessel

Figure 6 is the result of the location due to the acoustic emission test performed during the fatigue test on longitudinal defect vessel. Figure 6 (a) shows the location of 25 events during the first 3 fatigue test cycles. It does not show the location of artificial defects but shows the overall looks on the whole vessel. Such results are not shown in pictures but also in transverse defects vessel, 49 events in Figure 26 shows looks like a) on the whole vessel and it seems that signals were created on the weakest areas of the whole vessel when the first pressure was put. In the case of b), after the 4,000th cycle, in the 3rd fatigue test, 23 events were shown to be clustered around the artificial defect. As for the vessel with transverse defects, after the 4,000th fatigue test cycle, in the 3rd fatigue test, 12 events were created but they were all over the whole vessel so we could not show the location of the artificial defect. In the case of c), in the 8000th fatigue cycle, 108 events were clustered around the artificial defect and as mentioned in the explanation in Figure 4 more than 50% of the occurred hits were signals related to the artificial defect. Afterwards, events that occurred in d) –f) were those that mostly occurred near the artificial defect so we can acknowledge that the damage on the composite material is progressed around the artificial defect.
Figure 6. The result of source location with cycle for longitudinal defect:
a)0, b)4000, c)8000, d)12000, e)16000, f)20000

Figure 7 shows the surroundings of the longitudinal artificial defect after the 20000th cycle and shows that at the end of the defect, there is a matrix rupture progressing in a hoop-direction and although not clear in the picture, at the end of the depth in the artificial defect, delaminating was observed on the overall defect. In the case of vessel with transverse defects, after the 8,000th fatigue test, less than 1 event was created and the location of the artificial defect could not be shown clearly.

On the other hand, after the 20000th fatigue test, in the burst test, the location of the burst is marked in c) of Figure 6 and events are also observed in a), d), e), and f). The source of the acoustic emission signal is assumed to be the fatigue rupture in the weak areas of the steel liner rather than in the composite material. The final burst in the case of the longitudinal defect accompanies matrix rupture and delaminating as mentioned above during the fatigue test and burst test so the whole vessel area, which is the length of the defect, is thinner in terms of thickness like the depth of the defect and thus is weaker than other areas and it is thought that it burst at the final burst location in which the fatigue rupture occurred in the steel liner.

Figure 7. Longitudinal defect and matrix crack after 20000 cycle fatigue test
3.2 The rise time during during fatigue cycles

Figure 8 shows the relationship between the amplitude of the signal occurring during the early three cycles and the rise time, and can be clearly distinguished as around 10 $\mu$s and over 100 $\mu$s and the grey mark shows the rise time while holding the load during the three cycles and also at 90 $\%$, which is the highest, has a rise time of about 10 $\mu$s. Generally while load holding, it can be inferred that there is likely to be growth of an existent crack rather than initiation of a new matrix crack and thus can be said that it is a growth of crack around 10 $\mu$s. And the rise time of AE signal which occurs during the initiation of a matrix crack can be said to be more than 100$\mu$s. This accord to the result that the rise time of the AE signal occurring during the initiation of matrix crack during the burst test is around 100 $\mu$s and that the rise time of the AE signal occurring during the growth of the crack is around 10 $\mu$s. [10]

On the other hand, in the case of a sound cylinder, after the 4000$^{th}$ fatigue test, the average rise time noticeably decreased and increased little up to the 20000$^{th}$ test. After the 4000$^{th}$ fatigue test, there are not many initiations of new matrix cracks and you can see the growth of the cracks created in early stages. On the other hand, in the case of cylinder with defects, the average rise time of related hits for events occurred during the first three fatigue test was 56 $\mu$s and afterwards decreased to 34 $\mu$s after the 8000$^{th}$ cycle and increased to 82 $\mu$s about after the 12000$^{th}$ cycle and then decreased again.

Figure 8. The rise time distribution during initial 3 cycles for sound vessel

Figure 9 a) shows the relationship between the amplitude of the signals of events occurring during the first three cycles of the vessel and related hits and rise time and is clustered around 10 $\mu$s in the figure and is also scattered around 100–500 $\mu$s. It is judged that the initiation and growth of matrix crack will happen in weak areas of the overall vessel. Especially, a higher rise time can be observed when the source forms a cluster around the defect as shown in b), c), e), f) of Figure 8 than when the source is scattered overall on the vessel like a) or d) so the growth of cracks around the defect has a lower rise time than the initiation of cracks.

On the other hand, after the 4000$^{th}$ fatigue cycle, the average rise time of the signal occurring in defect vessel are shown to be higher than the average rise time of signals occurring in sound vessel.

In the case of a sound vessel, the growth of individual cracks occurs far away in other cracks. But, in the case of vessel with defects, the growth of multiple cracks occurs around the defects because the elastic energy needed for the growth of matrix crack in the vessel with defect is smaller than that of sound vessel. And generated signals overlap with other signals. Therefore, the rise time of signal is extended.
Figure 9. The rise time distribution of hits during initial 3 cycles for longitudinal defect vessel: a) 0, b) 4000, c) 8000, d) 12000, e) 16000, f) 20000 cycles
Figure 10. The rise time distribution of hits during initial 3 cycles for sound vessel:
   a) 0, b) 4000, c) 8000, d) 12000, e) 16000, f) 20000 cycles

Generally, in order to analysis of frequency, we use wideband sensors to detect signals, and analyze by the Fourier transform of detected signals. However, because the sensitivity of wideband sensors fall behind resonant sensors, signals are also detected using resonant sensors and the frequency is calculated by rise time, duration, and count. Frequency by calculation was used and analyzed in this research because resonant sensors were used for the source location.

Figure 11 shows the distribution of rise time on the amplitude of the signals occurred in the final burst location. There is almost no rise time above 100 μs and is dispersed around 10 μs. It can be thought that the rise time which occurs during the growth of steel liner fatigue crack is similar to that during the growth of matrix crack.
3.3 Burst test after 20000 cycles fatigue test

We burst the vessel with two types of artificial defect after carrying out 20000 cycles fatigue test on a sound vessel and continuously increasing the pressure where the burst pressure is 590~615 bar with the difference in the pressure of the vessel were within 5% and thus was irrelevant to the existence of defects.

Generally, 20000 cycles of fatigue is equivalent to a vessel used for more than 50 years if you are to put pressure on the vessel once a day although, of course, in the case of a real gas vessel, gas is used as a pressure medium so it may be different from the case in which machine oil is used as a pressure medium, but if the vessel with artificial defects and sound vessel were tested in the same conditions, the burst pressure is shown to be almost the same. Thus, in the case of the size of artificial defect used in this research, the direction of defect is shown to have almost no effect on the life of the vessel. Figure 12 is a picture that shows the burst location in the vessel with the artificial defect. As shown in the picture, we can see that in the case of a vessel with a transverse defect, the final burst location is in the general burst location (cylinder and head area) for a well-constructed type II vessel. However, in the case of a vessel with a longitudinal defect, in both vessels, the final burst location was within the transverse vessel in which the defect was located. We think that this is because in the case of the longitudinal defect, the wrapped fiber is cut in 3 mm depth and in 50 mm length so the effect in which the thickness of the composite material is big, but in the case of the transverse defect, the fiber is cut only in 3 mm depth and in 3 mm length so the effect is small.

In this research, we cannot precisely know how much the depth of the defect has to be in order for the final burst pressure to change; however, the direction of the defect and the final burst location do have a correlation and we can infer that the longitudinal defect has a bigger effect on the final burst location.

Figure 11. Distribution of rise time in the final burst location

Figure 12. Position of artificial defect and bursting: a) sound, b) longitudinal, c) transverse
Table 2. The burst pressure by defect type

<table>
<thead>
<tr>
<th>Defect type</th>
<th>ID</th>
<th>Burst pressure (bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal</td>
<td>a-1</td>
<td>590</td>
</tr>
<tr>
<td></td>
<td>a-2</td>
<td>610</td>
</tr>
<tr>
<td>Transverse</td>
<td>b-1</td>
<td>605</td>
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<tr>
<td></td>
<td>b-2</td>
<td>590</td>
</tr>
<tr>
<td>Sound</td>
<td>c-1</td>
<td>605</td>
</tr>
<tr>
<td></td>
<td>c-2</td>
<td>615</td>
</tr>
</tbody>
</table>

4. Conclusion

After manufacturing a sound cylinder and a cylinder with artificial defect for the CNG vehicle fuel tank, we executed acoustic emission test during fatigue test and came up with the following conclusion.

(1) The rise time of the AE signal occurring during the initiation of matrix crack during the burst test is around 100 μs and that the rise time of the AE signal occurring during the growth of the crack is around 10 μs.

(2) There is a correlation between the direction of defect and the final burst location and the longitudinal defect had a greater effect on the final burst location of the cylinder rather than the transverse defect.

(3) Acoustic Emission Signal, which occurs during the fatigue test, occurred more in cylinder with defects rather than in sound cylinder, and as the number of fatigue test accumulated, the number of hits increased more in cylinder with longitudinal defects than in those with transverse defects.

(4) In the case of cylinder with longitudinal defects, events were clustered around the artificial defect and more than 50% of the occurred hits were signals that were related to artificial defects and the source location was precisely found on the defect location but in the case of cylinder with transverse defect, events rarely occurred and even if they occurred, the source location relevant to a defect did not match.

(5) Cylinder with two types of artificial defects (longitudinal and transverse) and a sound cylinder was put in 20000 fatigue test and the pressure was continuously increased and then was burst, the burst pressure was 590~615bar and the differences in pressure on the cylinder were less than 5% and was not relevant to the existence of defects.

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