INTEGRITY EVALUATION OF GLASS-FIBER REINFORCED PLASTIC VESSELS BY LAMB WAVE AE ANALYSIS

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Abstract

Integrity evaluation of glass-fiber-reinforced plastic (GFRP) vessels has become an important problem with the long-term aging of in-service vessels in corrosive environments. We proposed a method for estimating the integrity of aged GFRP vessels utilizing the sheet velocities and developed a simple method for exciting and measuring the Lamb waves. Applying this method to GFRP vessels in service, the sheet velocity measured was found to correlate well to the bending strength of the aged members. We successfully utilized it for the health monitoring of the vessels. Next we monitored AEs during the bending test of the aged members and determined the threshold tensile stress to cause internal damage. We also monitored AEs from the manway located near the bottom of a vessel in service. AE activity was found to be closely correlated to the residual strength estimated by the sheet velocity.

Keywords: GFRP vessels, Integrity, Lamb waves, Sheet velocity, Residual strength

1. Introduction

Glass-fiber-reinforced plastic (GFRP) vessels have served well for over 30 years in various chemical industries because of their excellent corrosion resistance and low price. GFRP vessels, however, tend to lose their strength due to degradation, such as hydrolysis reaction, oxidization, environmental stress cracking and so on. Although the GFRP vessels are designed to have enough strength, with the safety margin of about 10, catastrophic disaster occurs if the degradation is severe. Figure 1 shows an example of failed FRP vessels in our company. We have several hundreds of GFRP vessels, which have been used for more than 20 years. Hence, the integrity evaluation of these GFRP vessels is becoming an important maintenance issue.

Fig. 1 An example of failed GFRP vessels, used as steam condensate tank. (left) overall view; (right) Cut-out GFRP wall part from around the failed side manway.
GFRP vessels have been examined by standards-based visual inspection [1]. However, the lifetime of GFRP vessels cannot be predicted by the visual inspection because sub-surface degradation tends to occur without remarkable change of the surface. In addition, deposits on the inside surface makes the visual inspection difficult.

Other inspection methods such as radiography or ultrasonic testing also have difficulty for GFRP inspection because it is not easy to separate the defect-induced reflection waves from those from fibers, filler and initial defects. GFRP vessels generally have own specifications about resins, thicknesses, service environment, laminated structures and fiber contents. Sometimes, even the vessel owners do not have the details of the specification, especially about the laminated structures. In addition, GFRP vessels have many initial defects caused during the construction. These make the prediction of residual strength and lifetime of GFRP vessels difficult.

The present author proposes to use the Lamb waves for estimating the residual strength of in-service GFRP vessels. We measured the sheet velocity of S₀-mode excited by pencil-lead breaking on the vessel surface. The sheet velocity does not show any direct relationship with the strength of the GFRP, but can estimate the strength of composite materials. Seale et al. [2] reported a correlation between the damages of composites with sheet velocities. Toyama et al. [3] studied effect of density of transverse crack and delamination length on the sheet velocities. Hence, sheet velocity measurement has become an effective tool to predict damage of FRP materials. We measured the sheet velocities of many aged GFRP vessels in service and then studied the relation between the sheet velocity and residual strength estimated by bending test. We used AE technique to monitor the progression of internal damage of aged members of GFRP vessels during the bending tests. Advanced AE analysis for fracture-mode identification was used. [4, 5] Finally, we evaluated results of AE monitoring of two GFRP vessels in service. There observed a good correlation between the degradation predicted by sheet velocity and AE activities.

2. AE Monitoring and Sheet Velocity Measurement for the Aged Members

2.1 Test Specimens and Experimental Procedures

Test specimens were from the shell wall taken from a failed GFRP vessel. This vessel (Fig. 1) was used as steam condensate tank for 16 years. The structural layer of the vessel with the thickness of ~14 mm is produced by hoop filament winding with isophthalate unsaturated polyester resin. The interior corrosion layer of ~1-mm thickness is constructed by Novolac vinyl ester with chopped E-glass mats (450 g/m²). The vessel collapsed from cracks around the side manway. The cause of this accident is considered as the strength decrease by hydrolysis reaction of resin and by environmental stress cracking. New specimens, whose lamination structure is the same as the failed vessel, were prepared for comparison.

Bending strengths of these specimens σₜ₉ were measured by three point bending tests based on JIS K7055. The sizes of bending test specimens are 30 mm × 245 mm × 15 mm. Outer span distance of three point bending is set as 208 mm. AEs were monitored by four resonant sensors (PAC, type PICO, center frequency 450 kHz) mounted on the specimen surface. Here the member was set so as the tensile stress by bending is on the inner surface. This member setup is based on the deformation pattern of GFRP vessel with internal fluid pressure.

For a vertical vessel with side manway, hoop stresses by liquid head concentrates around side manway. Figure 2 shows the deformation pattern analyzed by FEM. The upper portion of the
manway bends to the inside by liquid head. The tensile stress acts on the inside of the shell wall around the side manway and failure initiates from there. The failure of the actual vessel initiated from around the side manway shown in Fig. 1(b). Therefore the bending load must be applied so as to give the tensile stress on the inner surface of the member. Also the longitudinal directions of bending specimens must be circumferential so as the hoop fibers bear tensile stresses. Directions of Lamb wave propagation for sheet velocity measurement should be in the circumferential direction.

AE sensors were mounted on the upper or outer surface of the shell wall, as shown in Fig. 3(a). Sensor outputs were amplified 40 dB by a preamplifier (NF Corp. 9913), digitized (Gage CS-12100, 20 ns sampling interval), and fed to a personal computer. Figure 3(b) shows experimental setup for sheet velocity measurement. In order to measure the sheet velocities on site, we excited Lamb waves by breaking a pencil-lead. Here the lead breaking triggered the digitizer by a voltage change, which was applied between aluminum foil on the sample and the pencil lead via a 50-ohm resistor. The Lamb wave was detected by a PICO sensor mounted at distance $L = 130$ mm from the lead break. Both the voltage change and Lamb waves were recorded on digital oscilloscope (Adtek system science, AXP-DS01, 20 ns sampling interval). Figure 4 shows an example of detected Lamb waves. Sheet velocity was measured from the traveling time and distance.

Fig. 2 Deformation of GFRP vessel with internal fluid pressure analyzed by FEM. (a) side view and (b) top view.

Fig. 3 Experimental arrangements (a) Bending test with AE monitoring (b) Lamb wave measurement
Fig. 4 Detected Lamb waves at distance of 130 mm for a GFRP sample.

Fig. 5 Detected AE wave and its polarity distribution at bending test.

2.2 Test Result of Failed Vessel Samples

Figure 5 shows examples of AE waves detected during a bending test. These are typical Lamb waves AEs with weak $S_0$-mode and trailing strong $A_0$ mode. We classified the fracture types by analyzing the polarity distribution of first arrival $S_0$-waves. Two samples, i.e., (a) one from the failed vessel wall and (b) a new sample, were bent under the same condition. Figure 6 shows the load-deflection curves and cumulative AE events for samples (a) and (b). Upper two curves are the load-deflection curves and the lower two the cumulative AE counts. The new
specimen showed a pop-in at the load of 3.2 kN or ~50 % the maximum load. This pop-in is considered to be due to the fiber fracture in anti-corrosion layer. AEs were detected from 2 kN, and increased rapidly before the pop-in load. Above the pop-in stress, load increased almost linearly to 6 kN. For the failed vessel wall sample (a), the load-deflection curve showed many load drops. At the load of 2.7 kN, the first and largest load drop was observed. This is the ultimate bending load of the wall member. This value is less than a half that of the new specimen. Total AE event counts from the failed vessel wall is less than a quarter of those from the new sample. First AE was detected at the load approximately 50% of the maximum.

Figure 7 shows the separate plots of the cumulative AE counts from Mode-I and Mode-II fractures classified from the polarity distribution of first arrival $S_0$ waves. It is first noted that the number of Mode-I AEs is three times larger than that from Mode-II AEs for the new specimen (b). In contrast, the Mode-II AEs are one-third larger than Mode-I AEs for the failed vessel wall sample (a). It is also noted that Mode-I AEs from failed vessel wall is smaller than new specimen (b). Less Mode-I AEs from failed vessel wall is considered to be due to prior fiber breakage by environmental stress cracking. Fibers pull out due to weak interfacial strength between the fibers and matrix in the failed vessel wall appears to be the reason for higher Mode-II signals.

Next we measured the sheet velocity ($C_e$) of the two samples. They were measured as 3.87 km/s for failed vessel specimen (a) and 4.87 km/s for new specimen (b). The velocity is decreased by 1 km/s by the degradation in the failed vessel wall specimen. Thus, the sheet velocity is can be used for estimating the degradation. To confirm this on a larger database, we measured the bending strength $\sigma_b$ and sheet velocities $C_e$ for 23 samples taken from various aged vessels.
Every specimen has different thickness and laminar structures, but their detail is unknown. Figure 8 shows the plot of the bending strength $\sigma_b$ versus the sheet velocity $C_e$ of these 23 samples. Relationship between $C_e$ and $\sigma_b$ can be represented by equation (1). Correlation coefficient $R = 0.86$ was obtained.

$$\sigma_b = 171C_e - 477$$  

(1)

The data points shown in an ellipse are the results from the failed vessel wall. The threshold of sheet velocity to estimate the critical degradation condition appears to be at 4.00 km/s.

Fig. 8 Sheet velocities $C_e$ vs. bending strengths $\sigma_b$ of aged GFRP specimens.

3. Field Experiment for In-Service Vessels

From laboratory experiment presented above, Lamb-wave AE monitoring and sheet velocity measurements are expected to provide the residual stress or integrity of anti-corrosion layer of GFRP vessels. We monitored AEs of two GFRP vessels in service.
3.1 Test Vessels and Experimental Procedures

Two vessels were evaluated by AE and sheet velocity measurements. Dimensions of these vessels are almost identical. Capacity is 50 m³, with the inner diameters of 3000 mm, and 7900-mm height. Maximum thickness of the wall is 10 mm and the maximum liquid level is 7000 mm. Vessel A has been in service for 22 years. The stored liquid is a by-product of amino acid hydrochloride with pH = 0 at normal temperature. No agitator is installed in this vessel. During AE monitoring testing, the level of liquid is kept at 50 %. AE had been monitored for 3.2 x 10⁵ sec. Vessel B has been in service for 2 years. The stored liquid is a by-product of amino acid hydrochloride with pH = 0 at 60°C. An agitator with a diameter of 450 mm is installed from a side nozzle near the bottom. The agitator speed is 350 rpm. To keep the inside temperature at 60°C, a steam heat exchanger is installed from another side nozzle. During the AE monitoring, the level of liquid is increased from 0% to 84 %. AE had been monitored for 4.9 x 10⁵ sec.

Figure 9 shows the experimental setup for AE monitoring. AE monitoring system (Chiyoda Corp. C-AEAS 4ch monitoring system with total gain 60 dB amplifier and 100 kHz high-pass filter) is used. Four resonant type AE sensors with center frequency of 200 kHz and diameter of 5 mm were mounted on the upper surface of the bottom manway. Thresholds of all channels are set as 512 mV. To record AE waveforms, KEYENCE NR-500/HA-08 Wave Logger with 5 μs sampling interval is connected to signal output terminal of C-AEAS. Threshold of this wave logger is set as 2 V. Attenuation was measured as 1.7 dB/cm. The four AE sensors were mounted at the corners of a 250 mm × 200 mm rectangle.

3.2 Experimental Results

Table 1 shows the results of sheet velocity measurements and AE monitoring for vessel A and B. For vessel A, any degradation such as environmental stress cracking was not observed by visual inspection, in spite of 22 years service. Measured sheet velocity 4.61 km/s is higher than the threshold sheet velocity. No AE was monitored during approximately 4 days of measurement. For vessel B, overlap laminates between side plates and nozzles including the manway become white in color as shown in Fig. 10(a). In addition, pinholes were found over the whole anticorrosion layer. Their color becomes black due to the permeation of liquid as shown in Fig. 10(b). These defects appear to be produced from shoddy fabrication. These defects were repaired by grinding and laminating before AE monitoring. No significant defects inside the vessel are observed at present. The sheet velocity of vessel B is measured as 3.46 km/s and is lower than that of the failed vessel. We detected a number of AE from this vessel.

<table>
<thead>
<tr>
<th>Stored liquor Temperature</th>
<th>Agitator</th>
<th>Condition of corrosion layer</th>
<th>Sheet velocity Ce, km/s</th>
<th>Liquid level</th>
<th>AE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vessel A pH 0, Normal</td>
<td>None</td>
<td>No degradation</td>
<td>4.61</td>
<td>50% Constant</td>
<td>None</td>
</tr>
<tr>
<td>Vessel B pH 0, 60°C</td>
<td>φ500mm, 350 rpm, Whitening, Pinholes (Already repaired)</td>
<td>3.46</td>
<td>0~84%</td>
<td>100,199,743 Events</td>
<td></td>
</tr>
</tbody>
</table>

Figure 11 shows the change of liquid level (a), AE event rates (b) and AE energy rates (c) of the events whose source location is in the sensors zone. As can be seen from (b), no AE was detected during feed pump operation since a high-pass filter was utilized.
Fig. 10 Inside defects on vessel B. (a) Overlapping of laminate around the side manway. (b) Pinholes with permeation of liquid into the corrosion layer.

Fig. 11 AE parameters for vessel B monitored by the AE parametric analyzer.

The agitator of vessel B starts when the liquid level is higher than 30%. No AE events were detected when the liquid level was less than 30%. AE events and energy increased after the
Fig. 12 Typical AE waves for vessel B monitored. (a) Mode II signals at 48% liquid level, (b) Mode I signals at 84% liquid level.
liquid level reached 30% or the agitator was started. AE events and energy, however, decreased with an increase of the liquid level from 30% to 84%. As shown in Fig. 11(d) and (e), a large number of AE events with long duration and rise time were monitored during from 48% to 64% liquid level. Some waveforms of Mode-I and Mode-II, detected at 48% and 84% liquid level respectively, are shown in Fig. 12. Fracture mode was classified from the polarity distribution of first arrival waves. Cumulative AEs from Mode-I and II are shown as a function of time and liquid level in Fig. 13. Waveforms, unfortunately, could not be recorded due to the capacity of the hard disk from $2.1 \times 10^5$ s to $2.4 \times 10^5$ s. Figure 14 shows effect of liquid level on the duration.

As shown in Figs. 13 and 14, a large number of Mode-II AEs with long duration were detected when the liquid level increased from 48 to 60%. Mode-I AEs, however, increased after liquid level reached 84%. Duration of AEs above 84% level became short. Figure 15 shows relation between AE duration and maximum amplitude of Mode-I and -II AEs. Mode-I events are in the area surrounded by dashed curve, but so as most of Mode-II AEs. The details of these results are now under investigation. It is now apparent that AEs are produced from not only the original defects but also agitation accelerated damages.
4. Conclusion

The integrity of GFRP vessels was evaluated by means of AE monitoring and measurement of sheet velocities. AE monitoring during bending tests of aged and new GFRP plates and from vessels in service are attempted. Results are summarized below.
(1) The sheet velocity is well correlated to the bending strength of aged members. It is successfully utilized for the diagnosis of the health condition of the GFRP vessels.
(2) AE from aged GFRP during bending test was much less than that from new sample and emitted more Mode-II signals than Mode-I.
(3) AE monitoring of new and aged vessel in service was performed. Old but undamaged vessel in service showed high sheet velocity and no AE was detected. Contrary to this, a new vessel with agitator with visible defects, showed low sheet velocity and emitted a number of AE signals. A relation between the sheet velocity and AE activity was observed. The details of these results are under further evaluation.

References


