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BRIDGING ACOUSTIC EMISSION TESTING AND ULTRASONICS FOR FRP

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INTRODUCTION

The use of Fiber Reinforced Polymer (FRP) for vessels and piping in the chemical processing industry (CPI) started in the 1960's. From early in the use of FRP for corrosion resistant equipment, challenges have presented themselves as engineers had to develop new design and construction methods to suit the behavior of the material. Early design approaches included use of metal vessel design standards, material design that did not correctly consider the reinforcement, quality control of fabrication and assembly, transportation damage, and damage from over-stressing at proof testing following metal vessel procedures, coupled with in-service abuse, process upsets, and other structural damage. Unfortunately, the early legacy of these challenges was numerous FRP failures, sometimes injuring workers. In spite of the undeniable industrial benefits of FRP to the CPI, in the early 1970's some significant owners of FRP vessels placed a moratorium on its use until its reliability could be improved.

Since that time, engineering efforts have resolved the early design flaws and have resulted in good design and construction standards.[1,2,3,4] These standards are dynamic documents with systematic review and updates.

To remove the moratorium and continue using FRP vessels, a non-destructive testing (NDT) method was required to evaluate the structure of the FRP and ensure that the final commissioning steps of hydrotesting and proof testing did not cause any damage. In the 1970's, investigation started of Acoustic Emission (AE) as a test method. This investigation was completed by the Committee on Acoustic Emission from Reinforced Plastic (CARP), including participation from material suppliers, users, test equipment suppliers and FRP fabricators. CARP worked as fast as they could to produce a solution, which also meant that they worked independently of the existing AE community and without independent critical review that Universities can provide.

The result of the CARP studies was an approach that focused on three effects:

1. The "Felicity Ratio" is the ratio of the stress at which a specific level of acoustic emission occurs compared to the previously applied stress where the same level of acoustic emission occurred. This describes how damage to FRP from a testing load—such as water fill—can alter the acoustic emissions of the FRP when the load is removed and then reapplied. A Felicity Ratio less than 1.0 can often be encountered.
2. Acoustic Emissions that continue when loading is held constant, and
3. High amplitude emissions.

Since 1983, AE has been adopted by many FRP users and has also been incorporated into relevant codes and standards.[1,2,5] Some jurisdictions require that FRP storage tanks only remain in service if they meet the acceptance criteria from periodic AE testing.

Each AE result is unique and does not depend on past results, nor does it predict future changes in the FRP.

This article is written to provide a brief case study of an AE test of an FRP storage tank. It begins with a description of the FRP tank being tested and the results of the test, which are used to illustrate how AE results can be combined with an attenuation-based ultrasonic technique that has been shown to provide reliable prediction of changes to FRP from service conditions. We then go on to provide further background of acoustic emission testing and relating the background to the test results. Ultrasonic testing was used to investigate the tank further along with conclusions about the cause of the AE results. Finally, a method is proposed to combine acoustic emission with the ultrasonic method described in my previous IJ article[6] to ensure reliable long term operation.

CASE EXAMPLE

New Jersey is one of the jurisdictions that requires periodic AE testing of FRP storage tanks. This study involves a tank that underwent AE testing in accordance with "Standard Practice for Acoustic Emission Examination of Fiberglass Reinforced Plastic Resin (FRP) Tanks/Vessels."[5] A FRP tank used for storing phosphoric acid required AE testing after 10 years in service with no maintenance problems, leaks, or external damage reported. To prevent the acid from dissociating, heating was necessary to keep the temperature at the required level. The tank had external electric heating panels that were held in place by an FRP wrap. Between the panels, the thin (about 1mm thick) FRP band was in contact with and possibly bonded to the shell. Over the panels, insulation was placed. There was no access to the outer surface of the tank shell because it was covered with insulation under the cladding. **Figure 1** shows the outer construction of the tank.

This was the first time an AE test was performed on this tank. No AE testing was completed for this tank when it was new. The inspector for the AE test was qualified by a certifying authority.

AE testing requires that sensors be placed on the shell of the tank. In this case, they had to be placed on the outer surface of the tank shell. They could not be placed at the same location of the heating pads or on the insulation. To make contact with the shell, holes were cut into the insulation to provide direct access to the shell. Three of these holes are visible in **Figure 1**. **Figure 2** shows approximately where the sensors were placed. Holes in the insulation are visible at the middle elevation and lower level. Note that the heating panels were located between the bottom row of sensors (Row 1) and the middle row of sensors

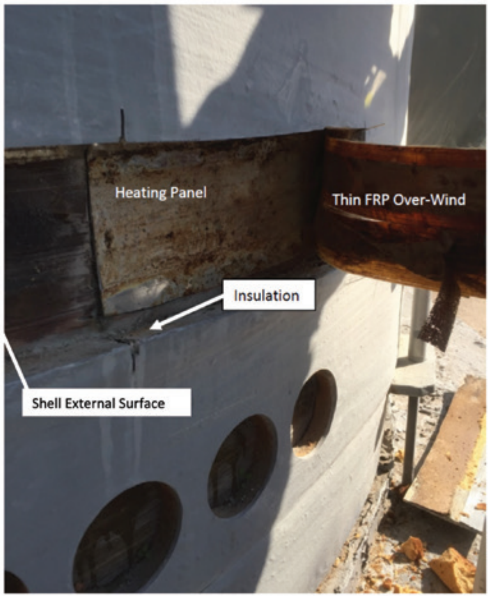

Figure 1. Tank Shell External Construction

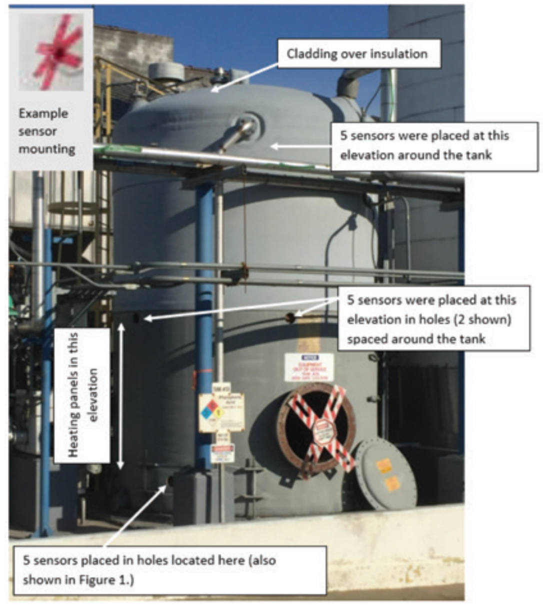

Figure 2. Sensor Placement

Tank Fill Level	Row										
			12		11		15		14		13
100%			0		0		0		0		0
87%			0		0		0		0		0
75%			0		0		0		0		0
50%	3		0		0		0		0		0
		8		7		6		10		9	
100%		100		100		100		60		80	
87%		0		0		0		80		0	
75%		0		0		0		0		0	
50%	2	0		0		0		0		0	
			2		1		5		4		3
100%			50		0		50		0		45
87%			55		0		60		0		60
75%			50		45		45		0		48
50%	1		45		60		90		60		0
						MANHOLE					

Figure 3. Summary of Detectable Emissions

(Row 2). Consistent with the standard for a first test, this test consisted of a single fill with no reductions of load during the test. Felicity Ratio, discussed above, is only applicable where load reductions occur during a test.

The standard [5] required that the tank be tested during a controlled fill procedure. At the end of the test, the data from all of the sensors was accumulated and evaluated according to the criteria listed in the standard. The criteria were: number and magnitude of detectable acoustic emissions, the time duration of emissions, and the number of high energy emissions.

The detectable acoustic emissions are summarized for each sensor and presented in table form in **Figure 3**. The sensor ID is in the shaded cells and the relative values associated with the different tank fill levels are listed. This table is for illustrative purposes only and is not the format required by the standard.

Note that all of the detectable emissions for the test occurred at the sensors that were adjacent to the heating panels.

These AE results were interpreted using criteria established in [5] for the count of the emissions that exceed a reference level during hold periods at different water fill levels and by the number of large amplitude emissions. The criteria are stated in Table X1.2 of [5]. Relevant damage mechanisms are discussed below.

Based on the AE results, the tank did not meet the acceptance criteria given in Table X1.2 of [5] and was removed from service as required by the regulator. The owner of the tank opted to investigate the tank further to help inform future decisions.

Before discussing additional inspections, some further background on AE is provided.

ACOUSTIC EMISSION BACKGROUND

As discussed above, AE methods for FRP tanks and vessels were developed by a concentrated effort to provide non-destructive methods for structural evaluation of FRP. Some of the earliest results reported are illustrated in **Figure 4**, which shows the results of testing 5 specimens of FRP that had been immersed in a chemical bath for between 1 day and 1 year. All of the specimens were loaded in 3-point bending, similar to ASTM D790 [7] while being monitored for acoustic emissions. The flexural modulus that was measured in the test was converted to a Percentage of Design Stiffness (PDS) using the equation below.[8]

$$PDS = \frac{Current\ Flexural\ Modulus}{Theoretical\ Modulus}$$

In **Figure 4**, the PDS value for each specimen is aligned with the value of the applied load where emissions started. Note that the values of PDS and load match very closely. In fact, the correlation is 0.94, where an exact match would be 1. The shape of the curve for load for emission onset seems to match the shape expected for long term creep performance of FRP.[9]

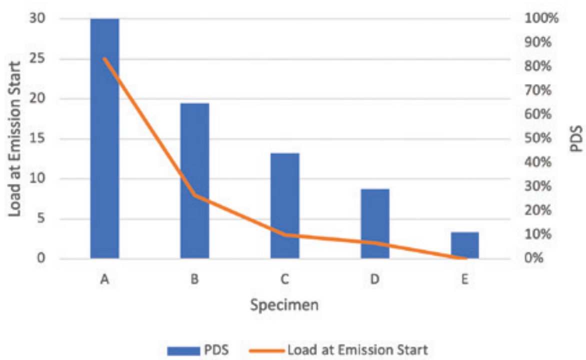

Figure 4. Comparison of Emission Onset Load and PDS

Many of the original studies that showed how AE could effectively detect structural flaws in FRP did so primarily by bending the FRP specimens. The results in **Figure 4** include heavily damaged FRP that has resulted in very low loads at the onset of emission. Normally, it is expected that the FRP tested for acoustic emissions will not be as heavily damaged as Specimens C, D or E.

Many Operators use intrusive confined space entry inspections to evaluate the condition of the corrosion barrier of FRP equipment. AE has not been used successfully to evaluate damage to corrosion barriers and the existing standards do not address this. It is reasonable to expect that no reduction in internal tank inspections will result from the use of AE.

Since the initial deployment of AE testing for FRP, research has continued to find enhancements and improve results. This research often reports the loads that are applied as a fraction of the ultimate, or breaking, strength of the FRP being tested. **Figure 5** summarizes this and includes the normal level of stress that is used for FRP tank, vessel and pipe design using modern standards and codes.

A significant question that investigators continue to struggle with is "what is the relationship between FRP strength and the AE test results?" The hope is that we can eventually determine the tensile strength so that improved service life predictions may be possible. There are a couple of approaches that have been discussed as possible answers to this problem.

One approach recognizes that creep failure of the resin often results in leakage and reduced ultimate strength. For most resins used in FRP, creep does not result in deformation of the resin, but

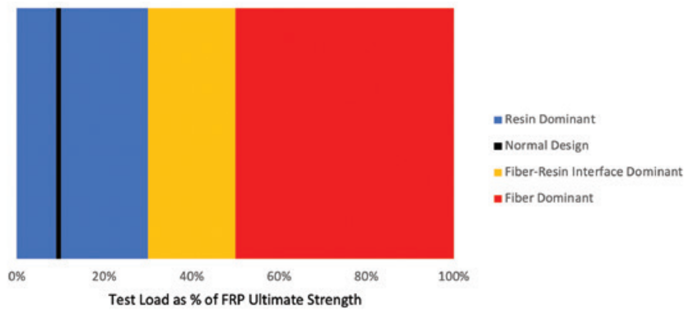

Figure 5. Loads Applied in AE Research

manifests as reduced elastic modulus so that failure of the resin occurs at lower stress. Significant creep can occur at ambient temperature and loads less than 50% of the ultimate load, where the stress is applied for an extended period of time. The same effect can be created by applying cyclic (loaded and unloaded) loads. Because creep occurs in the resin, it actually has little effect on the ultimate tensile strength except for FRP with low glass fraction. Creep does have a significant effect on the bending, or flexural modulus, of all FRP. **Figure 4** shows that significant creep, such as that caused by extensive corrosion damage to the resin, will increase acoustic emissions.

Attempts to relate tensile strength to acoustic emissions have not produced results that provide industry consensus, yet.

From the discussion above and **Figures 4** and **5**, note that creep of the resin—which reduces the bending properties of FRP—is the dominant change expected for the stress levels of FRP tanks and vessels in CPI.

Studies to date have not been able to find a relationship between AE test results and strength properties of FRP [2]. Other enhancements have been able to classify some emission data by the source of the damage that created the emission. More simply, to answer the question of what caused the acoustic emission—resin cracking, debonding of the resin from the fibers, laminate separation, or fiber breaks? Some answers have been found in determining the magnitude of the emission—research shows that higher emission magnitudes relate to greater energy release and appear to correspond to broken fibers in specimens during tests.[10] The lower magnitude emissions appear to relate to cracking of resin, debonding and laminate separation. In many cases, resin damage occurs before fiber damage because the resin normally fails at lower elongation (strain) than the reinforcement, especially for glass fibers. Many of the tests that were used to determine these factors took place at loads greater than the normal design environment for FRP vessels or piping in the CPI.

From the many AE tests conducted, the time that emissions arrived at different sensors was used to provide some insight into the location of the source. This approach has proven successful on numerous occasions to locate defects or discontinuities for repair when qualifying a new vessel.

IMPACT OF AE ON FRP RELIABILITY

Since AE testing and improved codes and standards were established, the reliability of FRP tanks and vessels in the CPI has seen significant improvement. In spite of the example listed above, the dominant use of AE testing has been for testing and qualifying new FRP vessels or tanks, especially when ASME RTP-1 [1] and ASME B&PV Section X [2] are used during design and manufacturing. When testing a new FRP vessel during hydro-testing or pressure-testing, passing the AE test is definitive proof that the vessel or tank is structurally sound. For in-service FRP, passing an AE test is also proof that the vessel or tank is structurally sound.

Standards for AE testing recommend placement of sensors where emissions will most likely be generated from discontinuities in the vessel. In adapting to requirements for AE testing on new tanks and vessels, manufacturers have learned how to maximize the success of testing by using improved manufacturing methods. These methods include best practices for installing fittings, joints, and, as often as possible, external attachments like the insulation or heating panels in the above example. It is important external attachments are not installed during the AE test to reduce the chances the test will fail due to something unrelated to the actual structural soundness of the vessel or tank, such as sound created by slippage of mechanical attachments.

One of the drawbacks of AE testing is that it does not provide information that can be used to calculate the rate that changes occur in the FRP as a result of service conditions. Nor does it provide any information that can be used to determine remaining service life. Each test is unique and does not relate to past tests.

CONTINUING THE CASE

Appendix M-8 of RTP-1 [1] stipulates in the general conditions that any discontinuities or defects that are detected by the AE test shall be evaluated by other techniques such as visual, ultrasonic, or others to determine if and where repairs are needed or retested as appropriate. This particular standard was not used to govern the test, so this requirement did not apply in this case. The owner of the FRP tank opted for further investigation of the tank. Since the tank did not meet the requirements of the regulator and was retired, destructive testing and specimen removal was possible.

Also note that the example tank had not ever been AE tested before, so there was no certainty that it would have met the AE requirements as installed.

A pulse-echo ultrasonic technique was used to evaluate areas of the vessel that could be sources of the emissions. [11], [6], The technique has been shown to provide accurate results regarding changes in FRP condition and can be used to make reliable predictions of remaining service life. The ultrasonic technique that was used is the one discussed in [6], based on quantitative attenuation analysis and transit time. There is no equivalent method incorporated by ASME. The major barrier to this particular application was the same as for the AE—the external insulation of the tank. Ultrasonic data was collected from the same locations as the AE sensors and responses were within normal ranges

This test was performed after the AE test was completed and the report was issued. Based on the information contained in the report, it was decided to concentrate on the vessel shell near the elevations of Rows 1 and 2 of sensors. No visible discontinuities were apparent on the internal shell in these regions. From **Figure 1**, the construction of the external shell led the investigator to believe that sources of acoustic emission could be from the shell due external attachments and not closely related to the manway or nozzles. To investigate the structural condition of the tank shell, ultrasonic readings were taken from the areas of the shell near or under the FRP over-wind, just above Row 1 and from the elevation of Row 2.

In operation, heat from the heating panels was applied to the outer surface of the FRP shell and conducted through the FRP to heat the acid in the tank. FRP is a poor heat conductor, so the heating panels had to generate fairly high temperatures to drive the heat into the inner surface of the tank. Looking at **Figure 1**, the FRP surfaces are all darkened from the temperatures applied and the amount of darkening indicated to the inspector that the FRP near the outer surface probably underwent additional curing.

Readings from the shell showed some abnormalities that were measured and quantified to determine that there was some discontinuity within the FRP related to the resin. The discontinuities were detected in the field but further analysis was required to complete the measurements since commercially available ultrasonic equipment does not have the capability to perform the calculations.

A specimen was removed near this reading for further analysis. The sample was sent to an FRP reinforcement supplier who had lab facilities. The specimen was tested using Dynamic Mechanical Analysis (DMA). DMA is a non-destructive test that can be used to determine if resin damage has occurred or if the resin is correctly cured. If resin damage is detected on the first try, attempts can be made to force additional curing of the resin so that the specimen can be retested to determine if the resin was not cured properly in the first place, or if irreversible damage to the resin has occurred – such as from chemical attack. From the testing, it was determined that the original resin in the tank was probably not fully cured and the heating panels had induced additional curing of the resin in the outer layers.

From this study, three things should be noted:

1. The tank worked without problems for 10 years even when the resin of the new tank was not fully cured,
2. The resin cure issue was unlikely to create significant acoustic emission and is not related to the AE test results, and
3. The upper section of the shell with no external heating was probably still under-cured and no acoustic emissions were generated from this region.

The ultrasonic results and destructive lab testing results both showed that the mechanical properties of the FRP were near 70% of the design values. No significant damage to the corrosion barrier was detected. The conclusion of this follow-up assessment was that the tank was fit for service with remaining life of at least 10 years.

BRIDGING AE AND THE ULTRASONIC TECHNIQUE

As mentioned above, the ASME RTP-1, Mandatory Appendix M8, requires that any discontinuities or defects that are detected by the AE test be evaluated by other techniques such as visual, ultrasonic, or others to determine repairs or retested as appropriate. [1] From the further ultrasonic investigation conducted in this study, it appears that this practice might have allowed the tank to continue in service. The ultrasonic method discussed is described in [6].

In the normal situation where discontinuities or defects in new tanks and vessels are detected by acoustic emission, ultrasonic techniques can be used to provide baseline information on the affected regions.[6] After entering service, these regions should be monitored periodically to ensure that the FRP remains within safe operating limits.

The FRP tank inspection procedure could be summarized as:

1. Where required by the buyer, perform AE testing in accordance with ASTM E1067 or ASME requirements.
2. If acoustic emissions from discontinuities or defects are detected,
   a. Document the affected region;
   b. Complete an ultrasonic survey of the affected region [6] and conduct a visual inspection;
   c. the survey shows explicit damage to the FRP, complete appropriate remediation and retest as required;
   d. If the survey does not show explicit damage, report the survey results as baseline for future inspections;
   e. Complete periodic ultrasonic inspections to monitor the region for changes.

Any of the subsequent ultrasonic test results, even when the AE test does not find any defects, can be used as the starting baseline for on-going reliability assessments.

Based on the author's experience with a wide range of FRP structures using this ultrasonic method, this approach will likely result in reduced cost for tank owner-operator. ■

For more information on this subject or the author, please email us at inquiries@inspectioneering.com.

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Geoff is the CEO and Founder of UTComp, Inc. His innovative company works globally to help eliminate uncertainty about the condition of FRP assets during production, delivery and in-service, allowing their remaining life to be determined. Geoff completed his engineering degree at the University of Waterloo, Canada in 1982, specializing in Systems Design Engineering. His decades of experience have helped him lead the way in the successful establishment of ultrasonic testing and fitness for service engineering for FRP composites. Geoff is a Member of the Order of Honour of Professional Engineers Ontario and a Fellow of Engineers Canada.