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Introduction

Fiber-reinforced thermosetting polymer (FRP) has been used successfully in many applications of pressure vessels, tankage, and piping. The ability of FRP to handle fluids and substances that are highly corrosive and potentially dangerous to personnel and the environment is undisputed. In some cases, service life exceeding 65 years has been documented.

There is considerable uncertainty about the capability of aging pressure vessels, piping, and tankage that is made from FRP to continue in service. Practices for how to detect and assess flaws and damage have not been consistent nor well-understood and accepted, and have often relied on subjective opinions that impose the expected behavior of metallics onto these materials. Damage to FRP from service conditions and material properties is usually completely different from damage that will occur to metal alloys, so using techniques and procedures developed for metals will produce unsatisfactory results.

When the fitness-for-service (FFS) is assessed using a Code such as API 579-1/ASME FFS-1, the engineer completing the assessment requires information on the type of material and the damage or flaw being assessed, along with the size or magnitude of the damage and the extent of the damage. The inspection data must come in a form that can be used for engineering analysis. This information is required so that the engineer can complete calculations to determine:

1. Is the equipment fit for service?
2. Is damage localized, or does it apply to the entire structure?
3. If the equipment is not fit for service, can it be re-rated?
4. Can repairs be made to address the damage?

For equipment made with metal alloys, the inspection techniques to be used for this are generally defined by codes such as ASME BPVC.V or other standards.

This article will explore the dominant damage mechanisms experienced by FRP during service. The article will then describe several detection methods and how they can be used to provide information on the size, magnitude, and extent of damage to FRP. The result of this article is to identify inspection information that is required to allow FFS assessment of equipment made from FRP.

In-service Damage to FRP

Damage to FRP occurs because of service conditions and may include: corrosion/degradation; ultraviolet damage to surfaces; stress; strain; abrasion; mechanical damage; chemical reactions and attack; operating and environmental temperatures; and others. Both the polymers and reinforcement used for most FRP are

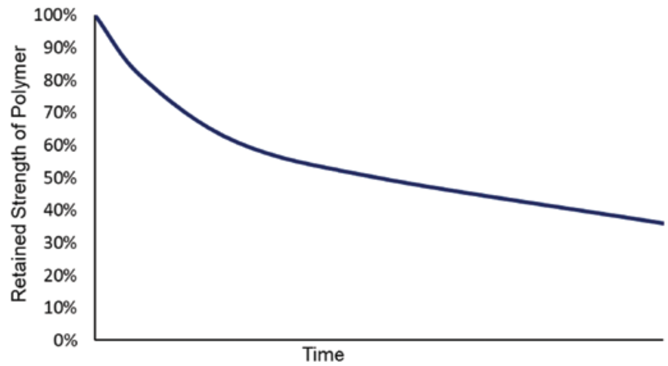

Figure 1. Viscoelastic Strength Reduction of Polymer in a Hydrochloric Acid Bath

non-linear viscoelastic materials, which have profound influence on their long-term behavior from service conditions. Physical properties such as elastic modulus and strength of viscoelastic materials undergo changes as a result of service conditions applied over time.

An example of how the strength property can change for a polymer that is often used in FRP is shown in **Figure 1**. **Figure 1** was produced from coupons immersed in a long-term hydrochloric acid (HCl) exposure test. In the figure, the strength of the polymer declines from this exposure from 100% when unexposed to 36%. Different chemicals and different polymers produce different results.

The reduced polymer strength results from reduction of both the elastic modulus and the elongation-at-failure of the polymer from the chemical attack, often referred to as corrosion, of the polymer. This strength reduction will also occur when only stress is applied to the FRP. When testing polymer performance, chemists often determine the change in elastic modulus of coupons by comparing the flexural, or bending modulus of coupons that have been exposed to the chemicals with coupons that have not been exposed to chemicals. The result is the *Retained Flexural Modulus (RFM)*, which is also described in Equation 1.

$$RFM = \frac{\textit{Flexural Modulus of Coupons After Chemical Exposure}}{\textit{Flexural Modulus of Coupons With No Chemical Exposure}} \quad \text{(Eq. 1)}$$

RFM provides quantitative data on damage that has occurred to the polymer in FRP.

Historically, inspection of industrial FRP equipment has relied on appraisal of the visible surface of the process-side of the FRP. For comparison with the results of **Figure 1**, **Figure 2** shows two examples of FRP using similar resins and cure systems. **Figure 2a** shows a new surface that has not yet entered service. **Figure 2b** shows a surface that has been exposed to hydrochloric acid for about 12 years. While the two images are slightly different, there

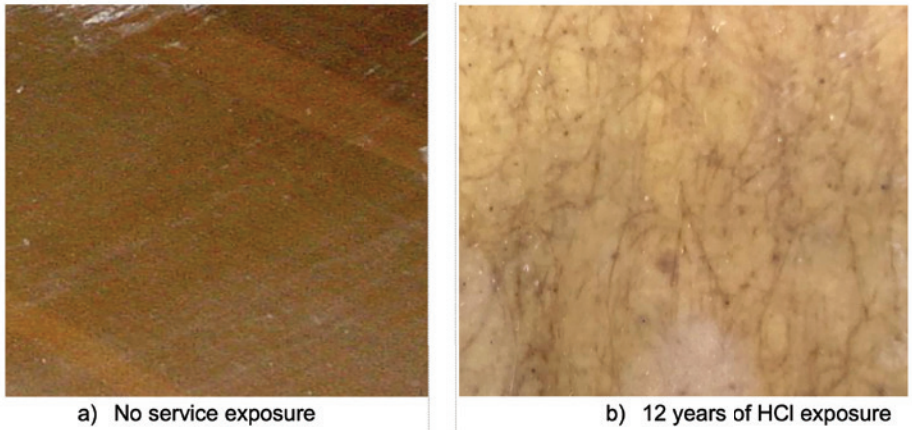

Figure 2. New and Exposed FRP Surface Appearance

is no way to identify the effect that the HCl exposure has had on the FRP. It is not possible to identify the change in the strength of the polymer from its appearance.

The reinforcement in FRP is embedded in the polymer, and its primary role is to add significant strength to the mixture. The polymer bonds to the reinforcement, protects it from service conditions such as chemicals, and serves to contain fluids. In many cases, such as with glass fiber reinforcement, the polymer will be damaged first and will crack before damage occurs to the reinforcement.

This example shows the need for inspections that can detect actual damage that has occurred to the polymers in FRP so that fitness-for-service of the equipment can be determined.

For industrial equipment such as vessels, tankage, and piping that is made from FRP, there are a number of standards and codes that are used to design reliable equipment. Examples of these standards and codes are ASME BPVC.X, ASME RTP-1, ASME NM.2, ASTM D3299, ASTM D4097, ISO EN 13121, and ISO 14692, as well as many others. These standards use the tensile strength of FRP for most of the design.

The tensile strength of FRP is the combined strength of the reinforcement fibers and the polymer. For much of the FRP used in industrial equipment, glass reinforcement takes 80% or more of the stress, and the remainder is carried by the polymer. The amount of elongation, or strain, that is created by the stress in the FRP is controlled by the reinforcement and imposed on the polymer. For new polymer, this stress and strain is easily handled. Just like for chemical exposure, long-term exposure of the polymer to stress and strain will also cause damage to the polymer. This damage also results in reduced strength. **Figure 3** shows an example of the change in polymer strength that occurs when FRP is exposed to constant stress and strain.

Note that the shape of the curve in **Figure 3** is very similar to the shape in **Figure 1**. In both cases, the polymer will crack well before the tensile strength of the FRP is reached. Often the cracks originate in damaged polymer and then stop or change direction as they encounter polymer that is relatively undamaged. An example of this is shown in **Figure 4**, where the arrows show how the crack direction is changing at the interface with a stronger

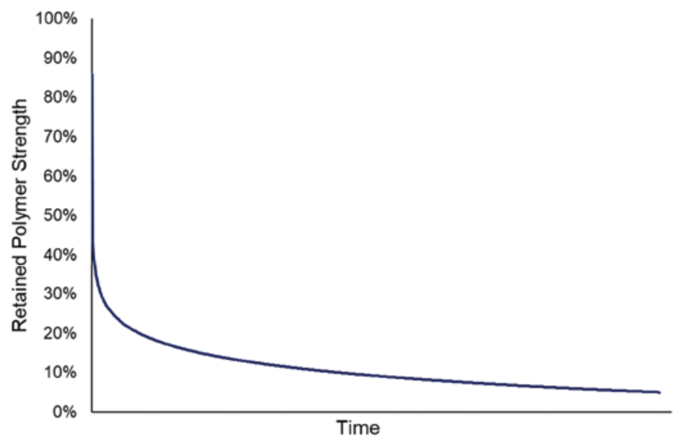

Figure 3. Effect of Stress and Strain over Time on Polymer Strength

polymer. Also, note for the example in **Figure 4** that there is no visible sign that predicts this change in direction. These cracks can then lead to chemical exposure of the reinforcement or leakage of the equipment, effectively leading to failure before the structure fails.

None of the construction standards for FRP equipment provide for in-service inspection of FRP equipment, nor do they provide information on changes that will occur in service. In the absence of any other document, it is common for some to specify the use of the visual inspection criteria from the standards, but as shown above, visual inspection often cannot reliably detect the damage that occurs to the polymer. In fact, overt defects and flaws are often unrelated to damage from service conditions and may have occurred during fabrication. These "built-in" flaws may or may not have any effect on its performance.

As shown, the damage that occurs to FRP from service conditions is not at all similar to the damage that occurs in metal alloys. The damage also has no relationship to the construction codes and standards used and is not addressed directly by them.

Fitness-for-service assessment of equipment requires inspection data that allows damage to be quantified and used by engineers to determine the condition and FFS of the equipment. While opinions and judgment may influence the engineer's result, it must be supported by data and work that shows that the recognized and

Figure 4. Crack Propagation

generally accepted good engineering practices (RAGAGEP) were followed. This will allow FFS assessments—from the most basic to the most complex—to be reliable and valid.

Detecting Damage in FRP

Visual inspection methods can identify the presence of leaks, cracks, blisters or visible damage, peeling bonds, changes in color of the polymer, and others. When these are observed, measurement is required to determine the extent and magnitude of damage.

Starting in the 1960s with the earliest use of FRP for aircraft components, NASA investigated nondestructive examination (NDE) for detecting damage and defects that could affect the reliability of these components. It became clear that NDE should not be defined solely by emphasis on detection of overt flaws, and it is necessary to extend it to characterize effects on material properties and thus detect the damage reported above.

NASA also found that the ultrasonic methods, if used properly, can provide this information. Most ultrasonic textbooks will provide a good description of how to determine the elastic properties of isotropic materials such as metal alloys and the polymers in FRP.

As shown above, damage to the polymers in FRP changes the elastic properties of the polymer. For FRP, three methods have evolved that will detect this damage:

- Acoustic Emission Testing (AE)
- Acousto-Ultrasonic Testing (AU)
- Attenuation-based Ultrasound (UAX)

Conventional ultrasonic testing (UT) can also be used to provide some supplemental information on damage within FRP. Fabrication practices, design, geometries, resin, and reinforcement all play a role.

These methods will be discussed below by considering the following:

- Standards or written procedures
- Criteria in ASME BPVC.V
- Inspector certification
- Calibration
- Outputs provide quantification of the damage
- Equipment operating conditions required for the test
- Ability to use outputs for further analysis.

Acoustic Emission Testing

Table 1 shows the discussion for AE.

Table 1. Damage Detection with AE

Item		Discussion
1	Standards or written procedures used	*AE* is applied using ASTM E1067 or ASME B&PVC.V
2	Criteria in Codes such as ASME B&PVC.V	Yes.
3	Availability of Inspector Certification	ASNT Certification is available to Level III.
4	Requirements for Calibration Standards	No calibration standards required.
5	Able to provide measurements that can determine damage as retained strength as in Figures 1 & 3.	No.
6	Equipment conditions required during detection activities.	Equipment must be out of service and disconnected. All external attachments must be removed. Uncontrolled loads such as from wind, traffic, etc. must be avoided.
7	Capability to use detection results for further analysis and remaining life prediction	No.

AE testing provides conservative results and provides locations of possible damage for follow-up with other methods. The method does not require any pre-assessment to detect overt flaws. If defects are found, ASTM E1067 recommends further evaluation, including use of other methods, such as ultrasound. Neither the test results nor acceptance criteria for the test provide *RFM* values.

The AE test report should include all the requirements of ASTM E1067:

1. Identification of equipment.
2. Equipment sketch or drawing with dimensions and sensor location.
3. Test liquid.
4. Test liquid temperature.
5. Test sequence.
6. Comparison of data from test with the Acceptance Criteria.
7. Identify the location of any suspect areas found.
8. Notes on any unusual effects or observations.
9. Dates of examination.

10. Name of examiners.
11. Instrumentation description.

Acousto-Ultrasonic Testing

Table 2 shows the discussion for AU.

Table 2. Damage Detection with AU

Item		Discussion
1	Standards or written procedures used	*AU* can be applied using 2 ASTM standards: ASTM E1495 and ASTM E1796.
2	Criteria in Codes such as ASME B&PVC.V	No.
3	Availability of Inspector Certification	Certification compliant with SNT-TC-1A is available. Certification for UT is recommended also.
4	Requirements for Calibration Standards	Calibration standards are required.
5	Able to provide measurements that can determine damage as retained strength as in Figures 1 & 3.	Yes.
6	Equipment conditions required during detection activities.	Equipment can usually be operating.
7	Capability to use detection results for further analysis and remaining life prediction	Limited to evaluation of the full thickness of the *FRP*.

Acousto-ultrasonic methods use an ultrasonic signal to excite the material and generate simulated acoustic emission events. As for ultrasonic testing, calibration is required using a specimen of the undamaged FRP taken from the part, as new and undamaged, that is being evaluated. During testing, the signals generated by the acousto-ultrasonic method are quantified into a value known as stress wave factor (SWF). The SWF can be used to calculate how much damage has occurred to the FRP.

The standard for this method recommends that the FRP be inspected initially using ultrasonic testing to identify locations with discontinuities that may affect the results of AU testing.

The AU test report should include:

1. Identification of the equipment.
2. Equipment sketch or drawing with dimensions and areas tested.
3. Tabulation of the test results.
4. Mapping of the testing results on three-dimensional representation or Cartesian projection of the equipment.
5. Classification of the AU SWF results into distinct categories. Some suggest using up to eight levels and a color code or grayscale for visual presentation.
6. A-scans of the ultrasonic readings taken.
7. Acousto-ultrasonic test equipment used.
8. Ultrasonic test equipment used.
9. Notes on special techniques used in interpretation, such as neural networks or spectral moments.

Attenuation-based Ultrasound

Table 3 shows the discussion for UAX.

Table 3. Damage Detection with UAX

Item		Discussion
1	Standards or written procedures used	*UAX* can be applied using ASTM C1332.
2	Criteria in Codes such as ASME B&PVC.V	No.
3	Availability of Inspector Certification	Certification compliant with SNT-TC-1A is available.
4	Requirements for Calibration Standards	Yes.
5	Able to provide measurements that can determine damage as retained strength as in Figures 1 & 3.	Yes.
6	Equipment conditions required during detection activities.	Equipment can usually be operating.
7	Capability to use detection results for further analysis and remaining life prediction	Yes.

The attenuation of ultrasound by FRP is very high. ASTM C1332 identifies that the approach used in the standard is not normally recommended for FRP. This method has been found to provide attenuation results when:

- low frequency transducers are used;
- the applied pulse to the transducer is square; and
- attenuation is determined using voltage of the applied and back surface reflections.

General UAX inspection, as described above, will require a calibration sample of the FRP that is being tested and at a known state. This could be obtained from a cutout from the new equipment. There is a patented process for UAX inspections [1] where the need for calibration is replaced by standardization. The patented process is based on experimental work that produced this calibration based on a standardized attenuation (see Reference 2). This expands the ability to inspect equipment that may have no calibration options available.

The UAX test report should include:

1. Identification of the equipment.
2. Equipment sketch or drawing with dimensions and areas tested.
3. Details of the calibration sample, if used.
4. A-scans of the ultrasonic transducer coupled to an elastomer delay line that is not in contact with any solid or liquid substance and taken at the inspection time and location. Each A-scan shall be provided in a form where the magnitude of received signals and elapsed time can be determined. Digital data of the A-scan image and settings from the ultrasonic instrument will normally meet this requirement.
5. Tabulation of the ultrasonic A-scans taken from the component, with location references mapped on a two-dimensional (Cartesian) projection of the component surface.

6. Mapping of the testing results on three-dimensional representation or Cartesian projection of the equipment.
7. Calculation of the estimated detected thickness of the FRP.
8. Ultrasonic test equipment used.
9. Notes on special techniques used in interpretation.

Ultrasonic Testing

Ultrasonic testing following normal practices is focused on detecting overt flaws and not providing material characterization. This does not provide much help for determining FRP damage. It can, however, provide information on the internal structure of FRP, which could then help with Assessment. **Figure 5** shows Figure 18c from Welding Research Council (WRC) Bulletin 601 : Fitness-for-Service Assessment of FRP Equipment.

Figure 5 shows an ultrasonic A-Scan from a commercially available flaw detector for a reading that was obtained from a cutout from an in-service FRP component. The reflection indication for "R3" represents the inner surface, or corrosion barrier surface of the *FRP*. Reflection at "R1" shows the location of the dark band in the section. Reflection at "R2" shows the interface of the light-colored FRP with the darker FRP near the opposite surface.

In conventional ultrasonics, reflections are generated from the applied pulses at locations where the acoustical impedance changes. For metal alloys, conventional practices assume that these changes are density changes—such will occur at a void or discontinuity that blocks pulse propagation. Acoustical impedance also changes when the velocity of pulse travel changes so that reflections will occur at the interface of two materials of the same density with different velocities of pulse travel. Ultrasonic investigation of damage to FRP has found that the velocity of ultrasound pulse travel will usually decline just as the attenuation increases when the polymer is damaged.

If the backwall at "R3" is in the reading, and "R1" and "R2" are present in a significant fraction of the readings from FRP, it is reasonable to conclude that "R1" and "R2" are not caused by flaws such as voids but are related to interfaces of polymer that have experienced different amounts of damage. Any time that the normal backwall reflection is not present would still correspond to a thinner section or a flaw. If only a few readings contain reflections like "R1" and "R2," it is also reasonable to classify them as flaws.

This approach can be used to provide an approximate thickness of the FRP between each of the reflections. One would assume constant sonic velocity and calculate the thickness from transit time.

A-scans, as in **Figure 5**, should be included in the AU report as stated above. Where an AE report has identified suspect areas, this approach should also be used for ultrasonic examination and the A-scans supplied. These conventional A-scans are not required when UAX is used.

This approach can be used without a calibration sample since the A-scan is provided with the transit time along the horizontal axis, and the engineer completing the assessment will be able to calculate the approximate thickness. The approach is also novel and different from conventional practices.

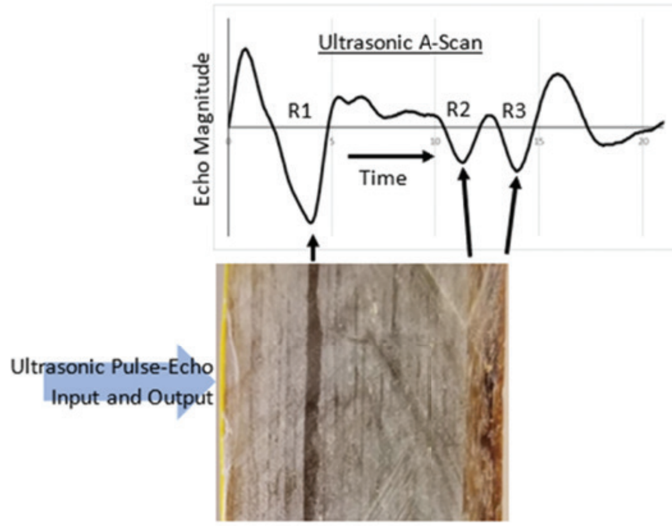

Figure 5. Ultrasonic Testing FRP

Conclusions

The engineer completing the fitness-for-service assessment of FRP needs to determine the extent of damage that has been done to the polymer and determine whether the FRP has retained sufficient structural integrity to continue in service. Assessment requires information on the magnitude and extent of the damage.

Inspectors are called upon to provide objective data that can be used in these assessments.

The four types of tests described in this article can be used to provide objective information for FFS assessments of FRP. Additional UT may be required when AE and AU are used.

The ultrasonic methods described in this article are novel and are not yet included in consensus standards. Keep an eye out for future articles that report the progress of these and other emerging detection and measurement methods. ■

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

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CONTRIBUTING AUTHOR

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Geoff is the CTO and Founder of UTComp, Inc., an innovative company working to help eliminate uncertainty about the condition of FRP assets during production, delivery and in-service, allowing their remaining life to be determined. Over his 30+ year career, Geoff has developed a high level of expertise in all aspects of the engineering, design, inspection and evaluation of FRP. Since 2006, he has focused his attention on the development of non-destructive tools for evaluating FRP and providing useful reliability information to end users. Geoff earned his engineering degree from the University of Waterloo, Canada in 1982, specializing in Systems Design Engineering.