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Introduction

Since 2017, Inspectioneering has published eight articles by this author and several by others that describe the inspection of equipment made from fiber-reinforced polymer (FRP). These articles have provided a range of technical information combined with case studies to describe the progress made in providing inspection data that can be used for fitness-for-service (FFS) assessments.

FFS applies to equipment that is structurally capable of providing its intended service for continued safe operation. The intended service refers to the parameters for which the equipment was originally designed and under which it is currently operating. In many cases, the actual operating conditions of FRP equipment differ from the original design conditions. In addition, the design and construction codes and standards used to fabricate FRP equipment are not applicable to in-service equipment, as this is explicitly stated in nearly all relevant codes and standards. Therefore, FFS assessments must incorporate inspection and engineering practices that extend beyond the scope of construction codes.

API 579-1/ASME FFS-1, "Fitness-For-Service," Code provides consensus methods to assess the structural integrity of equipment containing flaws or damage. The first 15 Parts (or Chapters) all deal with metal equipment and metallurgical conditions.

This article describes how engineering calculations for FFS will use inspection data for FRP assessment and identifies recommendations for future NDE equipment and training.

Inspection and FFS

Assessment of the structural integrity of equipment requires measurements from inspection that relate to damage, flaws, or the condition of the equipment's components. These measurements must provide data that inspectors or engineers can use following consistent procedures for assessment. Many will be familiar with the use of NDE to provide measurements of thickness, crack sizes, and other types of damage in metallic equipment. Certified inspectors have shown through training, exams, and performance that they can provide this data.

Modern standards for FRP equipment construction began to be used starting around 1969. Of course, there has been much learned and improved since then. Specifications for in-service inspection of FRP equipment often draw upon the inspection requirements for new equipment. At the time of this article, acceptance criteria are not always clear, and conclusions regarding the inspection can be subjective, with no available engineering analysis.

Non-metallic materials, such as FRP, have many differences from metal alloys. One of the most important items is that service conditions from chemicals and stresses will cause a reduction of the mechanical properties of both the polymer (or resin) and the reinforcement. In general, the polymer is affected more quickly and to a greater extent than the reinforcement, so its failure leads the way to structural collapse. This supports original inspection practices, which assess the condition of the corrosion barrier based on visual testing procedures.

Previous IJ articles by this author describe how NDE, UT in particular, provides data about changes to the polymer strength properties [1-7]. So far, three NDE methods have provided engineering data that can be used in FFS calculations: acoustic emission testing (AET), acousto-ultrasonic testing (AU), and attenuation-based ultrasonic testing (UAX).

As discussed, cracks in the surface with detectable width can be found with visual testing (VT) [8]. Further NDE with UT or other methods to determine the crack depth may be required in an assessment. Guidance on determining crack depth in FRP can be found in WRC Bulletin 601 [9].

Although the reinforcement fibers, glass or carbon fiber, provide most of the structural strength, NDE has not yet been found that identifies deterioration or allows remaining life calculation for this critical component. Since the polymer decays much more quickly than reinforcement, the conservative approach is to allow polymer condition to govern.

Crack Formation is the Key

For FRP, damage to the polymer (resin) is much more rapid than damage to the reinforcement. If the polymer protects and binds the reinforcement, then equipment constructed according to codes and standards will generally retain its structural integrity. Long-term load performance testing of FRP universally shows that cracks form in the polymer before any loss of integrity [9].

Cracks in the polymer generally form because the strength of the polymer declines due to service conditions (i.e., stress, strain, temperature and chemical exposure) and the polymer cracks while exposed to the stresses and strains expected for the design usually without any upset conditions. It is a form of creep. This condition is inevitable and is a fundamental property of the material and affects highly flexible rubber tires to very rigid epoxies as well as most reinforcement fibers. Changes in the appearance and surface hardness of the polymer can provide some indication of this, and that is part of the reason that visual inspection of corrosion barriers became so important for FRP.

Eventually, cracking will provide access for chemicals to attack the reinforcement and this could accelerate creep-rupture of reinforcement that affects structural integrity. Inspection needs to identify the risk and progress toward cracking of the polymer so

Figure 1. Practical cracking example.

damage to reinforcement will be minimized. The onset of cracking signals that it is time to start planning to rerate, repair or replace the equipment.

Consider a practical example. **Figure 1** shows two views of an FRP cutout where the process-side surface is cracked and darker-colored than the new surface. Of interest to the reader with FRP inspection experience, the hardness values using the standard Barcol 934 tester have increased while in service, preventing this old standby tool from providing any useful data. These cracks all formed during normal operation where stresses and strains were all as designed. When the section is examined in **Figure 1b**, the process-side damage appears to abruptly change, leaving FRP that looks like new. Furthermore, none of the cracks have propagated from the darker zone to the lighter zone, and in fact, many of them change direction.

An IJ article from 2020 describes how data on a range of conditions similar to **Figure 1** can be obtained using NDE methods and without destruction of equipment FFS from removing a cutout [5].

Identifying risk of cracking and predicting future condition requires data that goes beyond appearance and surface condition. Volumetric NDE is required that provides this data on the full thickness of FRP being inspected.

NDE for FRP Condition

Since the 1960s, it has been universally understood that attenuation of sound and ultrasound by polymers changes when the polymer is damaged. This follows the principle given at the beginning of every textbook on ultrasonic testing, where the attenuation factor is related to the elastic Young's modulus of steel. Furthermore, starting with NASA in the 1960s, it was concluded that overt defects and flaws, such as for metal alloys, are of little relevance to most FRP.

NASA also concluded that the best type of NDE to provide data on damage to FRP is ultrasonics. Work since the 1960s has provided a few methods that can be used. Each type of inspection is discussed below, including a description of the gaps for current equipment and training.

Acoustic Emission Testing

This type of inspection is well developed for FRP tanks and vessels. It is included in ASME B&PVC.V, ASME RTP-1, and ASTM E1067. It is stipulated for qualification of some ASME B&PV.X vessels and acceptance criteria are provided. The standard equipment provides all data directly. For piping, ASTM E1118 provides standard practice and does not include acceptance criteria. External specification of acceptance criteria for piping tests is required. In all AET, all background noise must be minimized and identified.

Training and certification for application of AET is available. Calibration specimens are not required, and calibration of the sensors is completed using the FRP to be tested. It is essential to use enough sensors to ensure that the acoustic emissions generated by damage are not missed.

The acoustic emissions detected by AET signal initiation or propagation of brittle cracking in the FRP, starting at very low levels. When the polymer retains good mechanical strength, the acoustic emissions will carry well. If the polymer has been heavily damaged, such as in the case of a process-side corrosion barrier, only acoustic emissions from the relatively undamaged FRP will be transmitted.

The standard practices for AET of FRP can be applied directly to in-service FRP to determine its fitness-for-service. When AET is applied to vessels, the standard practice provides acceptance criteria; however, these criteria are not published when applied to FRP pipes. AET results do not include any data that can be used for engineering calculations regarding fitness-for-service or remaining life.

Acousto-ultrasonic Testing

Standard practice for this type of inspection is provided by ASTM E1495 and ASTM E1796. Employer certification in accordance with ASNT SNT-TC-1A is possible; however, it is not included in the standardized training and certifications typically available. Acousto-ultrasonic equipment is not common. Ultrasonic flaw detector equipment can be set up for data acquisition, but the results are not available directly from the instruments, and post-processing of the readings is required. The ASTM standard practices do not include any methods to provide standardized data that could be used in engineering FFS calculations.

Calibration requires FRP that is exactly the same as in the component being tested, possibly from cutouts removed at manufacturing. At least one sample must be available for each component to be inspected and this will give conservative results. More accurate, yet still conservative, results will be obtained if multiple calibration specimens are used with varying damage levels.

AU data is known as the stress wave factor (SWF) and consists of numerical values. The actual raw magnitude of back-surface reflections could be used. The data from AU testing can be used in engineering calculations for FFS and remaining life. Criteria are not included in any of the inspection standards listed, and guidance for this is available in WRC Bulletin 601 [9].

Attenuation-based Ultrasonic Testing

This type of inspection is included in ASTM C1332. UT training and certification do not include all of the requirements. Additional employer certification in accordance with ASNT SNT-TC-1A is necessary. Modification is required to the procedure in ASTM C1332 to produce valid output for FRP. Ultrasonic flaw detector equipment can be set up for data acquisition. Still, the data is not available directly and requires some post-processing and calculations that combine data from several readings.

Calibration requires two or more specimens of FRP that are exactly the same as in the component being tested. The two specimens must have different amounts of damage.

UAX data output represents the attenuation factor derived from raw data supplied by a pulser-receiver. The attenuation factor can be used in engineering calculations for FFS and remaining life. Criteria are not included in any current inspection standards.

Recommended Changes to FRP NDE Standards

NDE of FRP for industrial and petrochemical use requires different approaches, training, and outputs than NDE of metal alloys. Defect detection has been successfully applied to FRP components, such as those used in the aerospace industry, where thin sections, higher stresses, tighter tolerances, and low fault tolerance dictate very conservative acceptance criteria. For most industrial applications, the FRP is much thicker, and the inspection needs are different, requiring volumetric methods as identified by NASA above.

The discussion above identified some new training and equipment needs that will help with FFS inspections of FRP equipment, as summarized below:

- Acoustic Emission Testing: No changes have been identified at this time.
- Acousto-ultrasonic Testing: Equipment is recommended that provides direct SWF output. Additional training programs are required for data acquisition and interpretation.
- Attenuation-based Ultrasonic Testing: Equipment is recommended that provides direct attenuation factor output for the procedure required for FRP. Additional training programs are required for data acquisition and interpretation.

Fitness for Service Process Overview

API 579-1/ASME FFS-1, "Fitness-For-Service," Code successfully uses a process that allows three levels of assessment, starting with the most conservative, which can usually be completed by an inspector or engineer on site, and progressing to more detailed and precise analysis which incorporates more details about the FRP involved and might involve specialist engineers. The first, most conservative approach can usually apply inspection data directly to determine fitness-for-service. An example of this would be a thickness test inspection.

One of the key parameters in API 579 is the Remaining Strength Factor (RSF), defined as the ratio of the collapse pressure of a damaged component to that of an undamaged component. The RSF is used to assess many types of flaws and defects, particularly those associated with volumetric metal loss such as corrosion and pitting. It has also been applied to evaluating crack-like flaws, including hydrogen-induced cracking (HIC). In general, a reduction in thickness leads to a corresponding reduction in strength. For FRP components, cracking of the polymer matrix is directly related to the RSF of the material, allowing a conservative FFS evaluation based on the condition of the polymer. Detailed procedures for calculating the RSF of polymers used in most FRP systems are provided in WRC Bulletin 601 [9].

A key output of an API 579-1/ASME FFS-1 assessment is also a prediction of the remaining life of a component or equipment. This is the time until the RSF is predicted to be at its minimum allowable level. This allows owner-operators to plan activities like the repair or replacement of equipment. **Figure 2** shows an example remaining life prediction for FRP equipment.

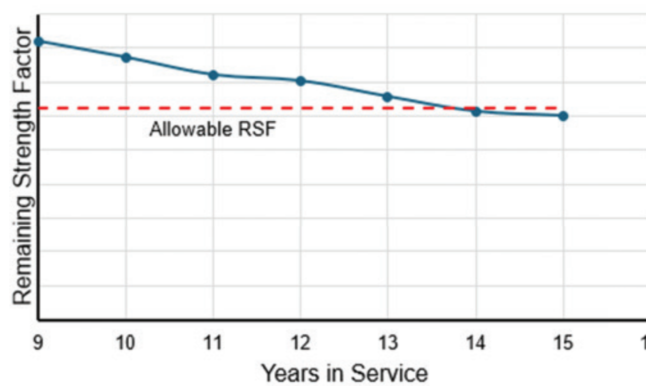

Figure 2. Remaining life curve.

A general outline of FFS Assessment using the NDE described above is summarized below.

Full Level 1 Assessment can be completed using any of AET, AU, or UAX. Acoustic emission testing directly provides FFS results and is widely accepted as a conservative method for providing a suitable Level 1 assessment. To provide a remaining life estimate, data from AU or UAX must be applied. The AU or UAX data will use standardized chart methods to calculate the polymer RSF from SWF or attenuation factor for remaining life calculations. The basis for these charts is outlined in WRC Bulletin 601, and they would also be included in the Code [9].

Additionally, details of inspections not covered by existing codes or inspection training and certification would be provided in API 579-1/ASME FFS-1, ensuring the integrity of the assessment can be maintained.

If the FRP is not fit for continued service at the Level 1 assessment, several options are available:

- Rerate the equipment by changing service conditions until the equipment is fit for continued service at Level 1
- Complete a Level 2 assessment
- Repair the equipment
- Retire the equipment

A Level 2 assessment may determine that the FRP is still fit for service before any rerating or repair is performed, provided more detailed analysis is included. This involves more engineering details that may not be available to an inspector, incorporating items such as reinforcement orientation, more details on service conditions, and different levels of damage that exist through the thickness of the FRP. In general, AET is limited to Level 1 because its acceptance criteria do not accommodate variations in FRP construction or through-thickness damage; therefore, the data used will come from AU or UAX.

The article "FRP Corrosion Barrier Inspection: Non-destructive and Non-intrusive Technique" explains how UAX can be used to identify different levels of damage that exist through the thickness of FRP [5].

As in Level 1, translating the values of SWF and attenuation factor will use standardized chart methods to determine RSF and the remaining life of the polymer.

If the FRP is not fit for service at Level 2 assessment, similar options as Level 1 are available:

- Rerate the equipment by changing service conditions until the equipment is fit for continued service at Level 2
- Complete a Level 3 assessment
- Repair the equipment
- Retire the equipment

A Level 3 Assessment would be completed if some data is available from testing or other field experience that could be used instead of the data that was used in the Level 2 assessment.

If the equipment is not fit-for-service at Level 3, then the options available are:

- Rerate
- Repair
- Retire

This article provides an overview of FRP inspection and how the resulting data can be incorporated into the Fitness-For-Service Code, API 579-1/ASME FFS-1. ■

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

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Geoff is the CTO and Founder of UTComp Inc., which 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 Systems Design engineering degree at the University of Waterloo, Canada in 1982. His work experience spans many chemical processing and nuclear fields. Since 2006, Geoff has focused his attention on the non-destructive assessment tools for evaluating FRP and providing useful reliability information to end users to resolve a consistent gap in support for end users of equipment made from fiber-reinforced polymer (FRP). Geoff is a member of the API/ASME Fitness-for-Service Joint Committee.