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BEHIND THE BULLETIN

Incorporating Non-Metallic Materials into API 579-1/ASME FFS-1

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Behind The bulletin

Incorporating Non-Metallic Materials into API 579-1/ASME FFS-1

This column is dedicated to highlighting key technical contributions found within the 70+ years of the Welding Research Council, Inc. (WRC) Bulletins.

Introduction

Users of the international standard for fitness-for-service (FFS) assessment, API 579-1/ASME FFS-1, can be assured that the procedures, methods, calculations, and conclusions have a sound technical basis. In many cases, the technical basis is provided via the Welding Research Council as WRC Bulletins. These publications have been a catalyst for a better understanding of damage to metal alloys, how to detect it, and its effects on the safety and reliability of pressure equipment. The FFS code has been prepared to provide reliable and practical methods that can be applied.

The application of API 579-1/ASME FFS-1 has been limited to equipment made from metal alloys – the dominant material used in the refining and chemical industries. However, non-metallic materials, including fiber reinforced polymers (FRP), are widely used as structural components of equipment, often where their corrosion resistance surpasses most alloys. Like steel equipment, the installed fleet of FRP equipment has, in many cases, outlasted its “design” life, and understanding of the safety, reliability, and economic performance of these assets is imperative.

This article describes the evolution of FFS assessments for equipment made from FRP, into the publication of WRC Bulletin 601, “Assessment of Existing Fiber Reinforced Polymer Equipment for Structural Damage.” WRC 601 provides practical information on engineering and damage of FRP that extends beyond what has previously been published. This bulletin is the first document that uses an engineering basis to assess the condition of in-service FRP equipment and to provide acceptance criteria for FFS.

All WRC Bulletins must be peer reviewed by individuals who understand the subject before publication. Reviewers for WRC 601 were located around the world and worked in material supply, fabrication, engineering, and end-user organizations.

This article will provide some history and describe how the engineering discipline used for API 579-1/ASME FFS-1 resulted in a coherent methodology that can be applied by inspectors, plant engineers, or specialists. The process followed by API 579-1/ASME FFS-1 uses inspection data to determine the structural mechanical integrity of a component. These assessments must be practical and achievable. The inspections and interpretations required for FRP may not yet be included in existing standards, but they must be available and suitable for incorporation into a standardized practice.

FRP for Industrial Applications

The FRP for WRC 601 consists of glass fibers embedded in a cured thermosetting polymer. The glass fibers are mixed with the liquid resin, which then cures into a solid, forming a structural material with the combined properties of the reinforcement and the polymer. FRP cannot be welded, and joining any parts requires an adhesive bond. FRP is elastic, but it has no plasticity – it cannot be formed by bending, and it does not yield.

FRP has been in use since about 1936. Its use as an industrial material started in the 1950s, and engineering methods and principles started to solidify in the 1960s. I am aware of one process vessel fabricated in 1957 that has been in aggressive chemical service for at least 65 years.

Several chemical producers led the way by establishing their own standards for engineering, fabrication, and quality control of FRP equipment. Many of these users contributed their experience to a range of consensus-based construction standards that are used worldwide. These standards apply factors of safety of 8 to 12.5 to designs based on lessons learned from experience. Using these high factors of safety allows design engineers to perform calculations similar to those used for metal alloys.

Some FRP equipment can be produced to comply with construction standards based entirely on the results of mechanical testing of a prototype. Units that duplicate the prototype can generally be used with no additional design documentation. This method is applied to some pipes and pressure vessels.

For FRP equipment to be used in corrosive services, most construction standards include a “corrosion barrier” on the process side. This is intended to protect the FRP with higher structural properties from damage due to the chemical contents. The corrosion barrier is usually incorporated during fabrication.

Manufacturers of the primary constituent materials – polymer resin and glass reinforcement fiber – have also systematically determined the behavior of these materials for exposure to a variety of service environments. Construction standards usually stipulate that knowledge from polymer manufacturers be used in selecting resins or polymers, and severe service conditions may be addressed by increasing the safety factor used in design.

The nondestructive testing (NDT) used for most quality control activities consists of tests to determine whether the surface resin has cured, visual appraisal of surfaces, dimensional checks, and, in a few cases, measuring thickness using ultrasonic testing. Standards for NDT, such as for alloy equipment, are not available. The only nondestructive tests currently required by construction standards during assembly are surface hardness testing for resin cure and visual testing.

In some cases, equipment is qualified by acoustic emission testing during the pressure test.

Although the design of FRP equipment might have some similarities to alloy equipment, production is completely different, and the damage that occurs in service environments is also different. WRC 601 takes a deep dive into the long-term behavior of FRP materials.

FRP Equipment in Service

A core principle of reliability engineering is that equipment in service should be inspected periodically so that developing damage can be detected early enough to allow cost-effective response: continue in service, re-rate, repair, or replace. Inspection of in-service FRP equipment utilized the same tests used for production quality control. Various NDT methods, such as those used for alloys, were tried but the standardized methods for metal alloys were not successful or widely adopted.

The core inspection methodology for FRP equipment became visual testing of the outer surface (e.g., for leaks, cracking, and signs of mechanical damage) and the process side surface for damage to the non-structural corrosion barrier. This methodology has been standardized by the National Board of Boiler Inspectors (NBBI) for pressure vessels manufactured in accordance with Section X of the ASME Boiler and Pressure Vessel Code (B&PVC.X). The visual inspection data can then be compared to the quality control requirements to determine FFS. For piping, API 570 "Piping Inspection Code" stipulates that new FRP piping should be inspected for acceptable installation, and no further inspections are specified. Some standards used for equipment outside of Canada and the U.S. provide for in-service inspection. These approaches are all based on the expectation that key structural properties, such as strength, remain constant.

In reality, inspection usually finds that the process-side corrosion barrier surfaces have changed and some cracks exist, and the inspector or engineer makes subjective decisions on their effect using personal experience and their best judgment. There are no published standards that guide those decisions.

In some cases, construction standards state explicitly that they do not apply to in-service equipment. Despite this, the same approach toward comparing inspection findings to the standard is used. What happens to FRP equipment such as piping, ducting, and small-diameter vessels when only the outer surface can be inspected? What about 8-inch (200mm) diameter reverse osmosis pressure vessels that operate up to 1,000 psi (70 bar)? What must be done to inspect and assess adhesive joints that seem to fail without warning? And what about the large fraction of FRP equipment that is in service at the time of this writing with insufficient documentation (e.g., construction details, its age, or whether standardized design was used to produce it, etc.)?

And a final question that comes from all inspections: What is the estimated remaining life to the point where repair or replace decisions must be made?

Damage to FRP from Service Conditions

The design approaches outlined in construction standards have proven to provide reliable FRP equipment to enter service. For all process equipment, service conditions can cause damage to the material and equipment. In the case of FRP, the approach to inspection came from understanding that some changes to the polymer in the FRP were visible, and the inspection focused on that. It has become broadly understood, starting with NASA in the 1960s, that damage to the polymer is the major contributor to changes in the durability of FRP – even when there is no chemical activity. Equipment will normally burst if the reinforcement fails, and it will simply leak if the polymer fails. An illustration of this is shown in **Figure 1**.

Figure 1 is based on long-term pressure testing of pipe, and it shows a comparison of the long-term behavior of glass reinforcement fiber to pipe leakage for pressure held in the pipe. A pipe burst occurs in the circled zone, and after that, at lower pressures, leakage usually occurs without any bursting. At the times when pipe leaks occur, it is clear that the fiber rupture line would only apply at much higher pressures.

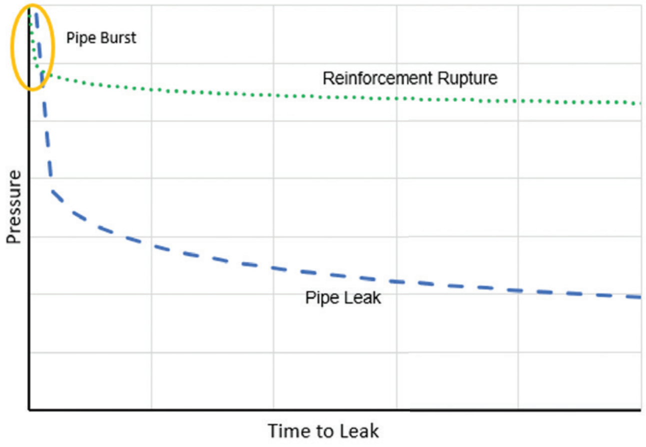

Figure 1. Long-term pipe pressure testing.

Both reinforcement and polymer experience a form of creep, known as relaxation, where the strength is reduced from both stress and chemical attack. The factors of safety of 8 to 12.5 are used to provide a margin for longer life. For both the polymer and glass fiber, the elongation at failure reduces, and the polymer strength loss is also due to the reduced stiffness of the polymer. The polymer loses strength much faster than glass fibers. The polymer will crack at the point where the reinforcement must

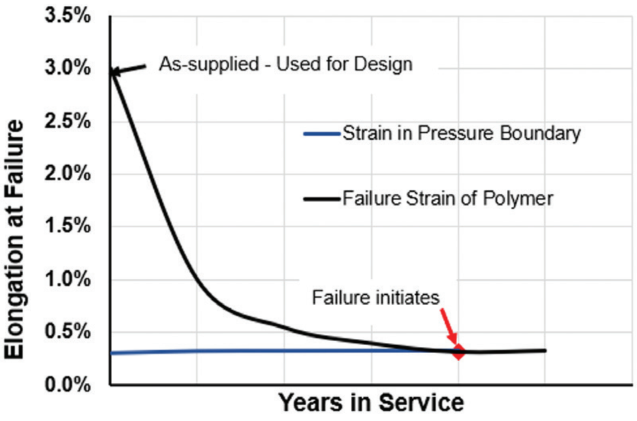

Figure 2. Progression to polymer crack formation.

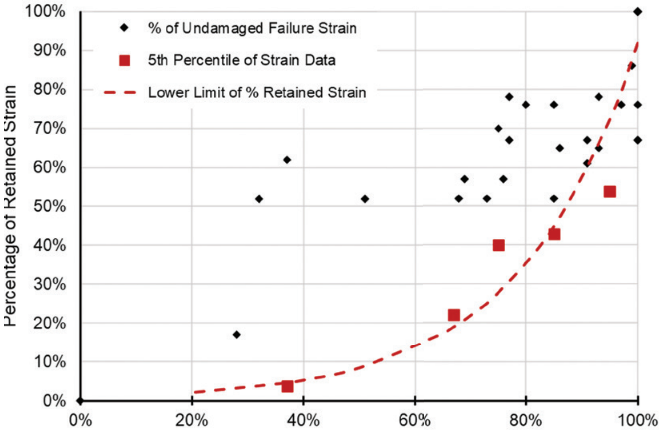

Figure 3. Failure strain and PDS.

stretch to carry the stress from service. This is summarized in **Figure 2**, which shows material behavior that is different from alloys in the elastic range.

The failure initiation point shown in **Figure 2** illustrates a conservative point where the polymer could crack and expose glass fibers to damaging chemicals, which may further weaken the FRP. The focus of FFS for FRP is on the condition of the polymer, which is the same focus that applies to the core inspections developed prior to WRC 601.

All of the details provided so far can be determined by destructive testing, which is not an approach supported by API 579-1/ASME FFS-1, since its goal is to preserve the FFS of assets rather than cut holes in them. WRC 601 goes on to describe how to detect damage with nondestructive evaluation (NDE) and use objective numerical data to determine the changes that have occurred for polymer elongation at failure.

Obtaining Objective Data

There is a long history of testing and verifying the polymers used for FRP, especially for process service in contact with chemicals that may cause damage. One of the most common tests is ASTM C581, which involves submersion of thin coupons in solution, then observing changes that have taken place at different exposure times. One of the tests used on the coupons measures the Young's modulus of the coupon in a 3-point test, per ASTM D790. This test provides direct information on changes that have occurred to the Young's modulus of the polymer. The value reported is the Retained Flexural Modulus. This directly shows how damage has changed the Young's modulus of the polymer. This is the polymer damage status (PDS), which can be calculated using Equation 1.

$$PDS = \frac{Bending\ modulus\ of\ tested\ coupon}{Bending\ modulus\ of\ undamaged\ coupon} \qquad \text{(Eq. 1)}$$

ASTM C581 does not include tensile testing of coupons, but some published experimental data completed this in addition to the retained flexural modulus results. This combined data is shown in **Figure 3**, along with a curve illustrating the conservative fifth percentile of the failure strain reduction.

It has been shown for many years that ultrasound pulse transmission is related to the Young's modulus of the material being tested. Since 2008, this principle has been used to provide a reliable PDS of the FRP in a component, using NDE. WRC 601 provides methodologies to use ultrasonic testing to obtain PDS, with some modifications to existing ASTM standards. At this time, PDS cannot be directly provided by any field equipment, and there is no reference to it in ASME B&PVC.V or other consensus sources.

API 579-1/ASME FFS-1 does not provide inspection procedures or methods. It does however stipulate specific inspection data that is required to allow FFS to be determined. In the case of FRP, the required inspection methods are not widely available, so WRC 601 provides the necessary background to develop them.

Calculations for FFS

API 579-1/ASME FFS-1 is based on using the remaining strength factor (RSF) to determine FFS of equipment. RSF is defined as in Equation 2.

$$RSF = \frac{Collapse\ load\ for\ damaged\ component}{Collapse\ load\ for\ undamaged\ component} \qquad \text{(Eq. 2)}$$

WRC 601 develops equations to calculate RSF using data that can be obtained from inspection: thickness, pressure regulation applied to the equipment, operating and design pressures, and other loads. Load information is included because it has been found in many cases that current uses of FRP equipment may not match their design.

Initial assessment can be done without detailed knowledge of the FRP construction that was used, nor of the polymer or reinforcement that was used. This makes it practical for personnel with limited exposure to FRP engineering to obtain initial FFS results. If equipment does not meet the FFS criteria at this initial level, specialists may apply more advanced methods and knowledge to find that the equipment is fit for continued service.

Acceptance Criteria

Objective and numerical acceptance criteria are required to establish FFS. **Table 1** provides an overview of the acceptance criteria.

Table 1. FRP FFS acceptance criteria.

Item	Acceptance Criteria
Leaks from any component.	None
Cracks with detectable width.	None
Loading and Pressure Management data is provided.	Yes
RSF	$RSF_{FRP} \geq RSF_{Allowable}$

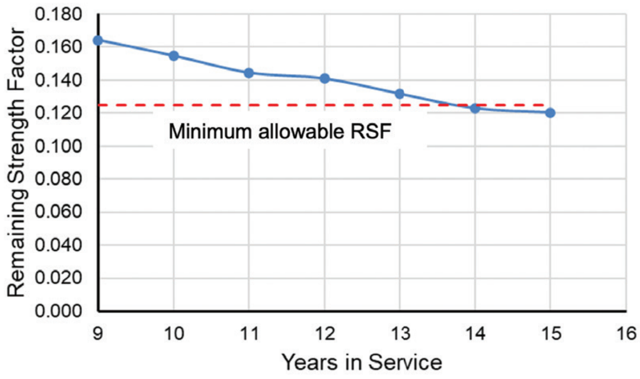

Figure 4. Example of remaining life projection.

RSF is then used to provide an estimate of remaining life, as shown in **Figure 4**.

Expanding FRP FFS Assessment and Inspection

The approaches described in WRC 601 can be applied to a wide range of FRP equipment used in the refining and chemical industries. Storage tanks, most pressure vessels, scrubbers, reactors, and piping can be assessed using the methods from WRC 601.

Some FRP equipment is designed using factors of safety that are less than 8. Examples of this include Class III pressure vessels under Section X of ASME B&PV, and some filament wound pressure vessels. Operation of these is in a stress-and-strain range where the approach used in WRC 601 may not be conservative enough, and other considerations will be required.

For applications of FRP where carbon fiber is used for reinforcement, long-term relaxation behavior of the carbon fiber is not well-documented and application of the methods in WRC 601 are not recommended.

FRP materials are increasingly used to strengthen and reinforce alloy components that have been damaged, and the reinforcement may outlast the alloy itself. These usually involve bonding FRP to the outer surface of the alloy. Application of this is included in ASME PCC-2. There is currently no inspection or assessment method that provides objective FFS in these cases.

WRC 601 describes the last stages of FFS assessment of FRP equipment and the inspections required. At the time of this writing, there are no consensus post-construction inspection standards, such as from API, ASME, or NBBI, that provide all of the data required to determine the remaining strength factor for FRP pressure equipment. As such, it is recommended that a complete consensus inspection standard for FRP pressure equipment be developed. ■

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

About the Author: *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.*