Proceedings of the ASME 2026
Pressure Vessels & Piping Conference
PVP2026
July 19-24, 2026, Anaheim, California, USA

PVP2026-183517

VERIFYING ALLOWABLE REMAINING STRENGTH FACTOR IN FITNESS FOR SERVICE ASSESSMENT OF FIBER REINFORCED POLYMER PRESSURE EQUIPMENT

Karelle Guiao[1], Mark Putt[1], Geoffrey Clarkson[1]

[1]UTComp, Inc., Cambridge, ON, Canada

ABSTRACT

API 579-1/ASME FFS-1 International Fitness For Service Code requires that assessment of pressure equipment use Remaining Strength Factor (RSF) to determine if equipment or components may continue to operate as intended by their design. For isotropic metal alloys, RSF is often determined by applying the effects of flaws or defects in the original design engineering. In the case of fiber reinforced polymer (FRP) materials, the material properties used for design treat mixtures of reinforcement and polymer as anisotropic, homogeneous materials. When service conditions are applied, damage accumulates at different rates to each constituent, in particular polymer and reinforcement, of the mixture. Consistently, failure of polymer usually occurs well before the reinforcement, and this forms the basis for RSF of FRP components. And when RSF is determined, what is the value of RSF that defines "End of Life"?

This paper will provide brief introduction to dominant damage mechanisms that apply to FRP equipment and the effect that they have on the structural behavior and RSF of the material. This will then lead to non-destructive evaluation of damage that allows RSF to be determined while retaining mechanical integrity. The question of determining the minimum allowable RSF value will be addressed using two different FRP failures: an atmospheric FRP storage tank and pressure piping. In both cases, non-destructive ultrasonic data was collected near the failure location and RSF was calculated for the components in accordance with Welding Research Council Bulletin 601. Similar RSF values were determined for both cases. From the findings of this work, it can be concluded that RSF for the polymer in FRP will provide reliable FFS assessment of FRP equipment. This paper also verifies and supports a conservative and effective allowable RSF value for FRP with practical failure cases.

Keywords: Remaining strength factor; fiber reinforced polymer; fitness for service

NOMENCLATURE

E_{fy}	Flexural Young's modulus of new FRP in the y-direction
E_{ty}	Tensile Young's modulus of new FRP for the membrane in the y-direction
f_{sp}	Failure strain fraction for polymer
F_d	Design loads
F_a	Actual loads
L_{acty}	Applied membrane load per unit width in the y-direction
L_{desy}	Design membrane load per unit width in the y-direction
M_{actx}	Applied bending moment during operation in the x-direction
M_{desx}	Design bending moment per unit width in the x-direction
PDS	Polymer damage status
R_d	Reduction factor for Young's modulus
RSF_{FRPy}	Remaining strength factor for FRP in the y-direction (axial) where both internal pressure and moments are applied
S_{dp}	Strength of damaged polymer
S_{np}	Strength of new polymer
t_a	Current thickness
t_d	Design thickness
t_{FRPs}	Thickness of the structural portion of the as-designed FRP
t_{strd}	Thickness of the structural portion from the detected thickness of the FRP

DEFINITIONS

AET	Acoustic Emission Method
AU	Acousto-Ultrasonic Method
CML	Condition Monitoring Locations

FEA	Finite Element Analysis
FRP	Fiber Reinforced Polymer
FFS	Fitness for Service
LCL	Lower Confidence Limit
NDE	Non-Destructive Evaluation
RSF	Remaining Strength Factor
RSF_{FRPa}	Allowable Remaining Strength Factor for FRP
UAX	Attenuation-based Ultrasonics

1. INTRODUCTION

Fiber Reinforced Polymer (FRP) materials have been in industrial use for vessels, piping, and other equipment since the 1950s. They are a composite of two main materials: a thermosetting polymer matrix often referred to as plastic, and fiber reinforcement, normally glass for most common industrial uses. The fiber reinforcement contributes strength and stiffness, and the polymer matrix contributes corrosion protection, leak tightness, and load transfer. The resulting material properties, as well as those used in design, depend on the orientation of glass reinforcement, proportion of matrix to reinforcement, and stacking sequence of layers with these variables. Each constituent experiences damage mechanisms from exposure to service conditions differently from metal alloys and at different rates from each other.

FRP experiences two primary damage mechanisms: damage to the polymer matrix and damage to the reinforcement. Unlike metallic alloys, both constituents, and therefore the composite polymer-reinforcement mixture, display non-linear viscoelastic behaviour in the form of creep and relaxation. Creep refers to irreversible deformation under exposure to service conditions over time, and relaxation refers to an accompanying reduction in Young's modulus. For FRP, this has been observed to also be accompanied by a reduction in strain at failure.

Welding Research Council Bulletin 601 (hereafter referred to as WRC601) provides the technical basis for assessment of FRP equipment [1]. This provides an engineering approach that allows Fitness for Service (FFS) to be determined based on objective non-destructive evaluation (NDE), along with the estimated remaining service life of FRP equipment. WRC601 is based on decades of empirical data and research which has shown that damage to the polymer matrix both precedes and occurs at a faster rate than damage to the reinforcement, resulting in failure of the polymer before that of the reinforcement, and so polymer condition drives FFS of FRP assets [1].

WRC601 shows how polymer damage in-service can result from mechanical loads, chemical attack, abrasion or erosion, ultraviolet radiation, and other factors [1]. These effects all contribute to viscoelastic creep and relaxation of the polymer, eventually leading to initiation of cracking when the reduced strain at failure reaches the induced strain resulting from service loads. Once the polymer has begun to crack, damage can accelerate by increasing the mechanical stress and exposing the reinforcement to damage from service conditions.

Damage to the polymer is shown by Polymer Damage Status (PDS) which represents the ratio of the Young's modulus of damaged polymer to that of undamaged polymer. This value is routinely reported for ASTM C581 tests for polymer chemical exposure and can be determined using 3-point testing to provide the Young's modulus in the through-thickness direction [2]. WRC601 also provides a curve with conservative correlation of PDS, and the reduced failure strain of polymer based on mechanical or chemical conditions [1].

Remaining Strength Factor (RSF) is the parameter used by API 579-1/ASME FFS-1 International Fitness For Service Code to determine whether equipment can continue to operate as intended by their design and is defined as the ratio of collapse load of the damaged component to the collapse load of the undamaged component [3]. The code contains parts for assessment of various damage mechanisms or flaw types, none of which can be directly applied to FRP equipment. For FRP equipment, in WRC601, RSF is based on viscoelastic relaxation or creep damage to the polymer constituent [1]. RSF calculations should also incorporate actual loading compared with design loading and any thickness changes, since this will undoubtedly affect current FFS. The general equation for RSF for FRP exposed to only membrane stresses due to pressure is given in Equation (1).

$$RSF_{FRP} = \frac{S_{dp} \times F_d}{S_{np} \times F_a}\left(\frac{t_a}{t_d}\right) \quad (1)$$

where S_{dp} is the strength of the damaged polymer, S_{np} is the strength of the new polymer, F_d is the design loads, F_a is the actual loads, t_a is the current thickness, and t_d is the design thickness.

The minimum allowable RSF provides the acceptance criteria that allows objective determination of FFS. For FRP pressure equipment, WRC601 shows that the minimum allowable RSF of $RSF_{FRPa} = 0.125$ provides a conservative value for the expected Design Factors or Factors of Safety used in these designs. This value is significantly different than for steel equipment, reflecting the differences in damage and material behaviour. The RSF values determined for the failure cases in this paper will be compared to the FFS acceptance criterion.

An FFS assessment is an engineering analysis of equipment to determine whether it is fit for continued service, relying on NDE techniques and analytical methods to assess flaws and damage. NDE techniques that will provide PDS are required to support assessment without affecting mechanical integrity of the equipment. The NDE techniques available for FRP are covered briefly below.

Acoustic Emission Method (AET)

This method involves subjecting equipment to pressure, vacuum or other service loads and using sensors to detect the acoustic emission caused by growing flaws. AET can be applied to FRP in accordance with ASTM E1118, ASTM E1067, or ASME BPVC.V [4] [5] [6]. The data provided by the technique results in a finding of Pass or Fail and, in case of a Fail, may result in identification of a suspect area that can be evaluated further with other methods. The results do not provide PDS results.

Acousto-Ultrasonic Method (AU)

This method may be used in accordance with ASTM E1495 or ASTM E1736 [7] [8]. It measures the magnitude of signal response to a small stress induced by an ultrasonic pulse in the material, using a reference specimen of the same material and construction with known mechanical properties. Results can be used to calculate PDS and RSF.

Attenuation-based Ultrasonics (UAX)

This method may be used by adapting ASTM C1332 **[9]**. It involves calculation of the signal attenuation of an ultrasonic pulse through the material, requiring at least two reference specimens: one in 'as-new' condition and one containing damage. Some methods incorporate additional resources that remove the need for reference specimens. Results can be used to calculate PDS and RSF.

This paper will go on to discuss two cases of failed components for which ultrasonic data was collected in the immediate vicinity of the failure location and the results were used to calculate RSF. The first case is an atmospheric storage tank, manufactured in 2005, with an elliptical bottom head that was partially supported by a concrete cradle underlying all but a small portion of the bottom head where a nozzle was connected. The failure occurred on the bottom head in the unsupported area. The documentation provided in support of the analysis indicated that the tank was manufactured to ASTM D3299, but the detected thickness of the bottom head did not align with the thickness required by this design standard [10]. The second case is a small piping stub, manufactured in 2004, of nominal diameter 250 mm (10") designed to ASME B31.3 [11] which failed around the full pipe circumference directly beside a flange. Information supplied by the owner in support of the investigation revealed that the flange was improperly mated to a raised-face valve, rather than to a full-face flange or with use of an effective spacer [11] [12] [13].

2. MATERIALS AND METHODS

2.1 Ultrasonic Readings Collection Procedure

Non-destructive ultrasonic readings were taken on the failed samples using an ultrasonic flaw detector, a 0.5 MHz transducer, and couplant. A standard delay line was used for the failed tank FRP samples, while a reduced-aperture delay (RAD) line was used for the failed FRP spool sample. A RAD line is a delay line with a narrow, rectangular face such that, when held parallel to the axis of a piping component, the face can be completely in contact with the part. Fig. 1a labels each of the samples from the failed tank as it is laid out based on the approximate location of each sample on the tank bottom and Fig. 1b labels each of the Condition Monitoring Locations (CMLs) along the failed spool sample. Readings of the failed bottom head were taken along the failed edge of each sample. Readings of the failed spool sample were taken circumferentially at the highlighted CMLs, avoiding any extra thickness due to secondary bonding. Readings taken at CML01 and CML02 are further away from the failure interface, while readings from CML03 were taken trying to maximize data from as close to the fracture as achievable.

2.2 Thickness Determination

Thickness measurements were taken using a caliper. A total of 38 measurements were distributed roughly evenly throughout all four samples of the failed tank, avoiding areas where additional material had been attached by secondary bonding. For the failed spool, a total of ten (10) measurements taken around the circumference of the failed end of the spool, also avoiding areas with extra thickness due to secondary bonding to the flange. The 90% Lower Confidence Limit (LCL) of the thickness was determined and reported, unless stated otherwise. This value represents the value of the average where there is less than 5% probability that the true average is lower. LCL of the thickness was used in the RSF calculations described below.

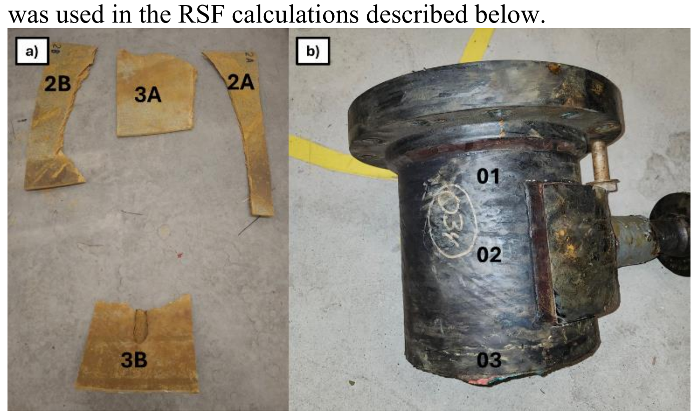

FIGURE 1: A) SAMPLES OF THE FAILED BOTTOM HEAD OF A TANK AND B) THE SAMPLE OF THE FAILED PIPING STUB.

2.3 Remaining Strength Factor (RSF) Calculation

In this study, UAX was used, as outlined above, to determine PDS. Similar to thickness, the 90% LCL of the PDS was determined and used in subsequent RSF calculations unless otherwise stated.

Equation (2) can be used to determine RSF for FRP where both internal pressure and moments are applied. This equation employs a simplified version of the general RSF equation in the axial direction (y-direction) outlined in WRC 601:

$$RSF_{FRPy} = f_{sp} \frac{\left(\frac{L_{desy}}{t_{FRPs}} + \frac{E_{ty}}{E_{fy}} \frac{6M_{desx}}{t_{FRPs}^2}\right)}{\left(\frac{L_{acty}}{R_d t_{strd}} + \frac{E_{ty}}{E_{fy}} \frac{6M_{actx}}{PDS * t_{strd}^2}\right)} \quad (2)$$

where f_{sp} is the failure strain fraction for polymer determined using LCL PDS based on Figure 14 of WRC601 [1], R_d is the reduction factor for Young's modulus due to damage, t_{strd} is the thickness of the structural portion calculated from the detected thickness of the FRP, t_{FRPs} is the thickness of the structural portion of the as-designed FRP, L_{desy} is design membrane load per unit width in the y-direction, L_{acty} is the applied membrane load per unit width in the y-direction, E_{ty} is tensile Young's modulus of new FRP for the membrane in the y-direction, E_{fy} is flexural Young's modulus of new FRP in the y-direction, M_{desx} is design moment per unit width in the x-direction, and M_{actx} is the applied bending moment during operation in the x-direction [1].

According to WRC601, FFS assessment may be performed at three levels [1]. As the levels increase, the level of conservatism for assessment decreases as a result of more precise data and thorough analysis. This study performs FFS assessment at Level 1. In Level 1 assessment, R_d is taken as equal to PDS and E_{ty}/E_{fy}=1.03 as conservative assumptions.

2.4 Mechanical and Simulation Modeling Procedures

For the failed bottom head, Finite Element Analysis (FEA) was performed using SolidWorks simulation. A curved flat plate equivalent to the unsupported elliptical bottom head was modeled and the operating conditions were applied. The parameters used for modeling and calculations, as well as their sources, are presented in Table 1. Material properties were taken from ASTM D3299 [10]. Bending moment was calculated from the stresses obtained from FEA simulations for both design and service conditions. These values were used in RSF_{FRPy} calculations in Equation (2). ASTM D3299 was also used to determine the minimum thickness required for a fully unsupported elliptical bottom head [10].

TABLE 1: PARAMETERS FOR THE FAILED ATMOSPHERIC TANK.

	Value	Source
Total tank height	13.7 m (44.8 ft)	Drawing
Diameter of tank	5.0 m (16.4 ft)	Drawing
Distance from overflow to top of tank	0.2 m (0.7 ft)	Drawing
Height of bottom dome	1.25 m (4.1 ft)	Drawing
Density of vessel contents (actual)	1 200 kg/m^3 (74.9 lb/ft^3)	Site Personnel
Measured range of gap between concrete supports of the bottom head	0.75-1.2 m (2.5-3.9 ft)	Site Personnel

For the failed piping case, ASME B31.3 was used to determine the maximum design bending moment of the flange using full-faced gaskets (M_{desx}) [11]. ASME B31.3 uses similar methods as ASME NM.2 Mandatory Appendix I and ASME BPVC Code Section X for the design of integral flat face flanges [11] [12] [13]. Alternately, ASME BPVC Code Section VIII Division I Appendix 2 was used to determine the maximum operating bending moment of the flange using non-full faced gaskets (M_{actx}) [14]. This method of calculation is not used for FRP piping design and is only used in this case to reflect how the flange connection was installed. Additionally, the attenuation of these bending moments through the length and thickness of the flange hub was considered using Timoshenko's method [15]. The flange and spool were Bondstrand 4000 piping components with a corrosion barrier thickness of 1.3 mm (0.05 in). As constructed material properties are unknown and the piping was qualified based on testing rather than design, conservative values for the material properties of the FRP spool and flange were taken from ASME NM.3.3 [16]. The gasket used in the design was Garlock STRESS SAVER © 370, and the bolts were ASTM UNS N10276. Other flange and spool dimensions were measured from the samples and outlined in **Error! Reference source not found.**. FEA was also performed using SolidWorks Simulation using the parameters outlined in Table 2. The design temperature and pressure were 93°C (199°F) and 552 kPa (80 psi), respectively. However, 1 MPa (150 psi) was used instead for design moment calculations as it corresponds to the minimum design pressure for the Bondstrand 4000 series. The operating temperature and pressure were 85°C (185°F) and 276 kPa (40 psi). The pipe contained 12% hydrochloric acid. The determined design and operation loadings were used in the calculation for RSF_{FRPy} described in Equation (2).

TABLE 2: PARAMETERS FOR THE FAILED PIPING STUB

	Measured Value
Inner diameter	259 mm (10.2 in)
Bolt circle diameter	362 mm (14.3 in)
Number of bolts	12
Bolt hole diameter	26 mm (1.0 in)
Flange outer diameter	406 mm (16.0 in)
Flange thickness	50 mm (2.0 in)
Flange hub length	26 mm (1.0 in)
Flange hub thickness	23 mm (0.9 in)

3. RESULTS AND DISCUSSION

3.1. Analysis of the Failed Bottom Head

Fig. 2 shows the failure of the atmospheric tank where an unsupported section of the elliptical bottom head collapsed near a nozzle. The bottom of this atmospheric tank was approximately 87% supported by concrete and compacted sand fill.

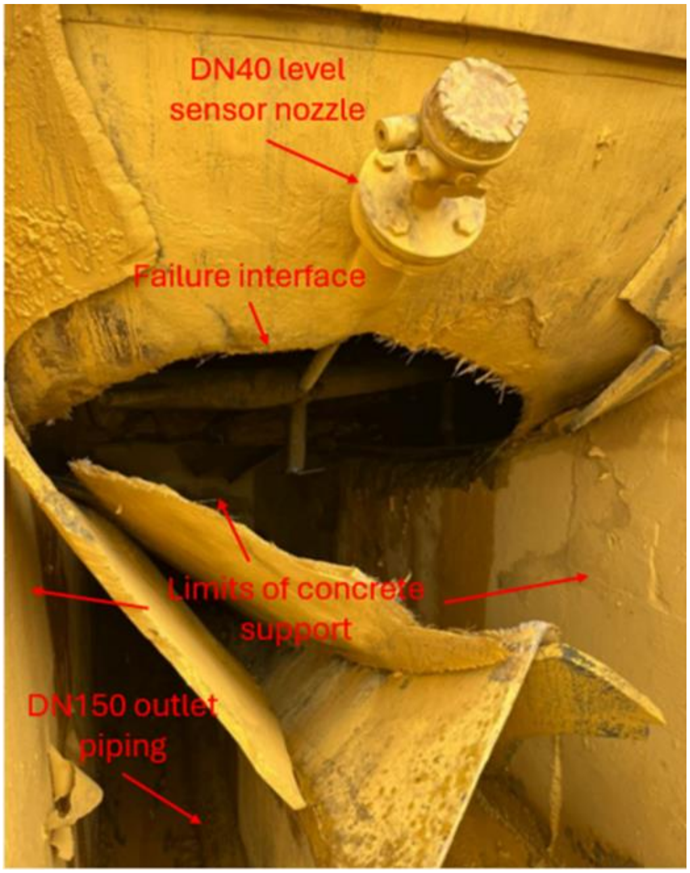

FIGURE 2: FAILURE OF THE PARTIALLY SUPPORTED ELLIPTICAL BOTTOM HEAD.

A closer look at the failure interfaces on both the left and right concrete supports are illustrated in Fig. 3. In the figure, there are several areas of clean fracture through the FRP thickness directly where the concrete support ends, with no glass fiber pull-out through the failure line. Contrastingly, in Fig. 2, glass fiber pull-out can be observed on the failure interface near the nozzle. The two interfaces display differing failure modes – the straight fracture along the concrete supports is indicative of long-term brittle fracture, while the inconsistent fracture near the nozzle is indicative of sudden tensile failure of FRP.

The samples of the bottom head measured an LCL thickness of 11.2 mm (0.44 in) and an average thickness of 11.5 mm (0.45 in). UAX results of each sample are summarized in **Error! Reference source not found.**. The PDS results of each sample were high and approximately within the same range. There was nothing of note to suggest that the polymer was heavily damaged at the inspected locations.

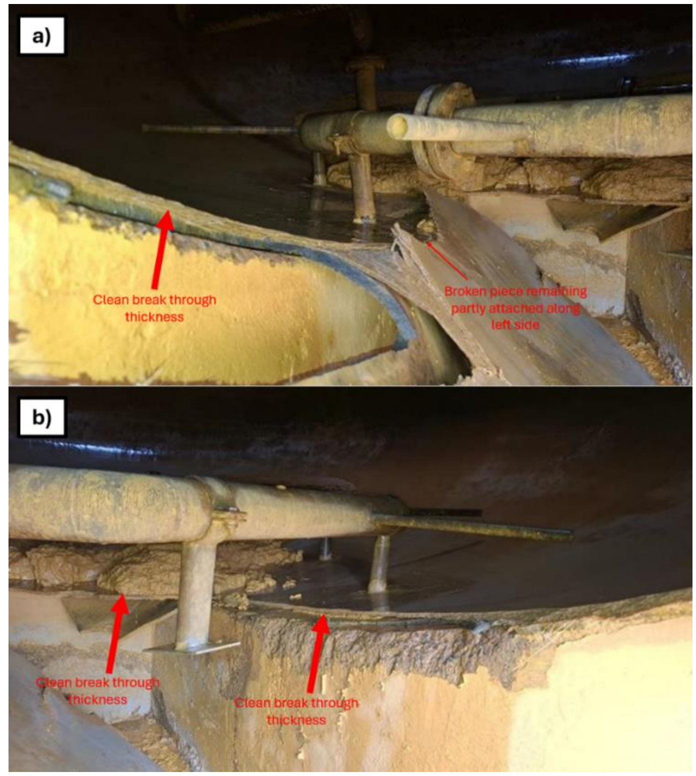

FIGURE 3: FRP FAILURE INTERFACE NEAR THE A) LEFT SUPPORT AND B) RIGHT SUPPORT.

TABLE 3: UAX RESULTS FOR THE BOTTOM HEAD.

Sample	LCL PDS	Average PDS	f_{sp}
2A	80%	83%	0.54
2B	84%	87%	0.60
3A	84%	87%	0.60
3B	76%	80%	0.48

In the drawings of the tank, it was suggested that the tank was designed to ASTM D3299 and NBS PS 15-69 [10] [17]. ASTM D3299 provides an equation to determine the minimum required thickness of a fully unsupported elliptical bottom head [10]. This equation is based on the tensile strength of FRP and does not consider completely supported nor partially supported bottom heads which introduce bending loads. Using this equation, the minimum required thickness for the bottom head of this tank is 38 mm (1.5 in). Note that for this bottom head configuration, design should consider bending stress as the dominant loading mechanism and the flexural strength of FRP. However, the determined minimum thickness from ASTM D3299 does not account for this.

To account for bending stress, the unsupported section of the bottom head was modeled, in Fig. 4, with its theoretical curvature using SolidWorks and the hydrostatic pressure head introduced by vessel contents and the fixed edges from the support configuration was applied. The nozzle above the failed bottom head section was not modeled since the failure interface at that location, discussed previously, indicated that failure did not initiate from there. For the average measured thickness, the maximum stress was 85.8 MPa (12.4 kpsi), located at the fixed edges. The determined maximum bending stress of the bottom head is significantly greater than the allowable bending stress of 15 MPa (2.2 kpsi) provided in ASTM D3299 [10]. The location of maximum stress areas in the model corresponds well with where brittle fracture was observed in Fig. 3, along the end of the concrete supports. These results indicate that the bottom head was inadequately designed.

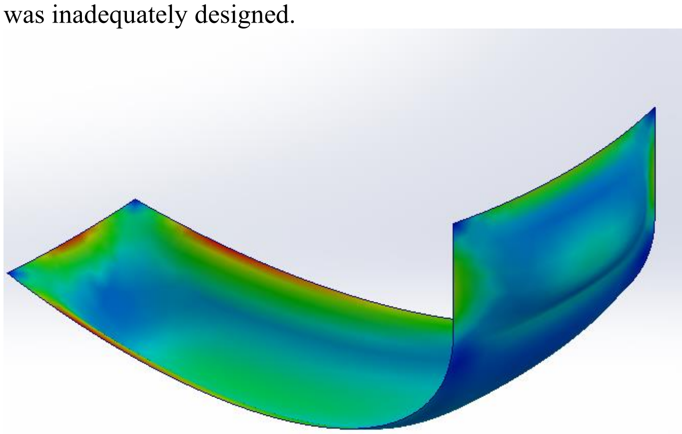

FIGURE 4: FEA MODEL OF THE UNSUPPORTED BOTTOM HEAD SECTION.

Given that the bottom head of the tank was improperly designed, the FEA model was adjusted and used to determine the pressure for which operating stresses fall within the allowable range of the design standard based on its known thickness. The pressure at which the allowable bending stress is reached was 27.7 kPa (4.0 psi). Meanwhile, the operating hydrostatic head of the tank was determined to be 158.3 kPa (23.0 psi). The influence of the disparity between design and operation on the FRP can be reflected by RSF. Using Equation (2) and the lowest LCL PDS measured in **Error! Reference source not found.**, RSF was determined to be 0.064, which is lower than RSF_{FRPa} [1]. Despite failing to comply with the standard it was designed to; the bottom head was in service until RSF reduced to point of failure twenty years later.

Since the bottom head at failure measured less than RSF_{FRPa}, this indicates that had the bottom head been assessed prior to failure, it would have been determined as not Fit for Service. The FFS criterion for RSF_{FRPa} serves as a conservative limit that could have seen the equipment repaired, replaced or re-rated at a realistic point before failure.

3.2. Analysis of the Failed Piping Stub

The failed spool component was attached to a flange which was connected to a butterfly valve, as shown in Fig. 5. The failure location on the spool was immediately located next to the reinforcement hub of the flange. It is important to note that while a full-faced gasket was used at the flange connection to the valve, the effective gasket area is equivalent to that of a non-full-faced gasket because of its connection to the raised face flange of the butterfly valve. The raised face flange only partially supports the full-faced gasket. All standards pertaining to FRP flanged connections required full-faced connections with full-faced gaskets.

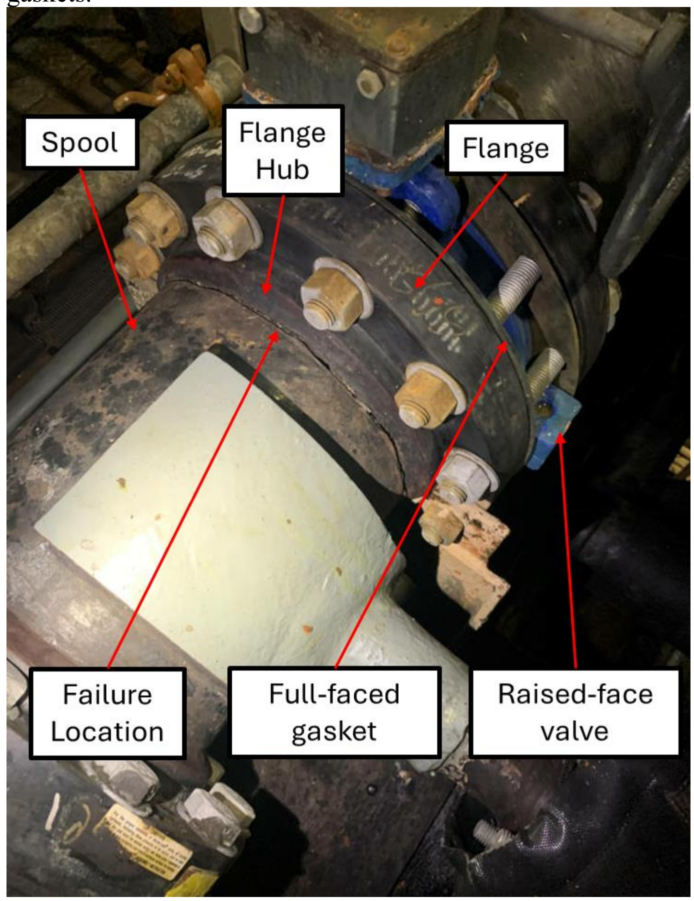

FIGURE 5: FAILURE OF THE PIPING STUB.

The failure interfaces on the flange and spool components are presented in Fig. **Error! Reference source not found.**a and Fig. **Error! Reference source not found.**b, respectively. On both interfaces, blue discolouration can be found. The source of the resin discolouration is unclear. The failure interfaces on the two components are notably very flat with little fiber pullout, indicating near-simultaneous circumferential brittle fracture of the spool.

The failed spool measured a thickness of 7.4mm (0.3 in). Ultrasonic readings were also taken along the spool according to Fig. 1b and the PDS results are presented in Table 4. The PDS for CML03 is significantly reduced compared to the PDS for both CML01 and CML02. This reduction in strength indicates that the resin at the failure location was experiencing more chemical and/or physical damage compared to other sections of the same spool further away from the flange. To determine whether this reduction in strength was enough to cause failure during service, RSF was calculated for the failure location using LCL PDS values from CML03. The attenuation of the moment at the flange through its hub was considered and the RSF of the spool immediately adjacent to the hub was determined to be 0.097 using Equation (2), which is less than the RSF_{FRPa} of 0.125 stated by WRC601 [1]. In the RSF calculation, for service conditions, it was assumed that the bolting for the flange connection was installed using the bolt load required for a full-faced gasket as required by ASME NM.2 [12]. However, the over-torquing of the bolts past this load was also likely due to poor installation practices.

TABLE 4: UAX RESULTS FOR PIPING STUB

CML	LCL PDS	f_{sp}
01	81%	0.55
02	80%	0.54
03	56%	0.28

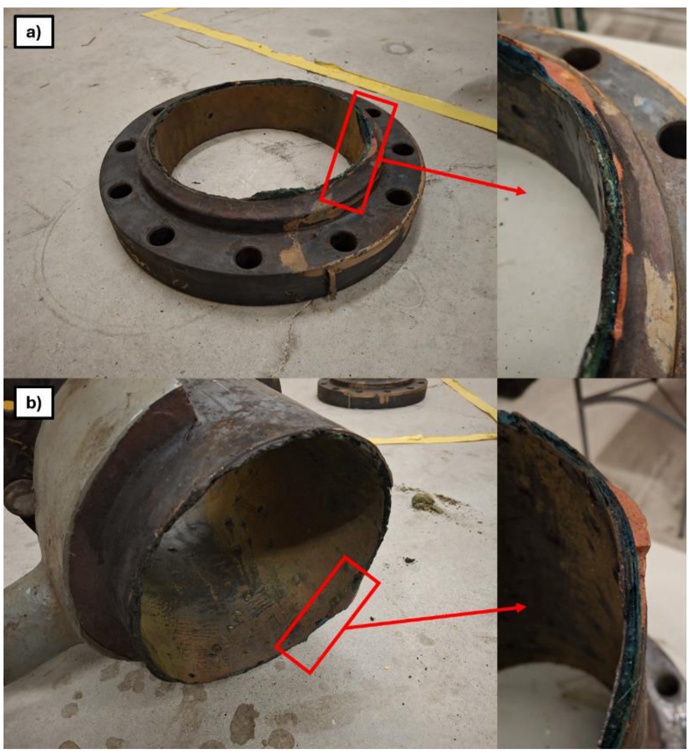

FIGURE 6: THE FAILURE INTERFACE OF THE A) FLANGE AND B) SPOOL.

The mechanical behaviour of the piping stub was also modeled in Fig. 7a and 7b for the design and operating conditions, respectively, to further illustrate the RSF findings. If the flange was installed properly with a full-faced gasket connection, the spool would experience a stress of approximately 20 MPa (2.9 kpsi) immediately adjacent to the reinforcement hub. Instead, because of its connection to a raised-faced butterfly valve, the spool near the flange hub was estimated to experience a bending stress between 60-80 MPa (8.7-11.6 kpsi). The raised-face condition significantly increases the amount of stress within the spool. Markedly, the model shows that the location of highest stress is between the flange bolt hole and the reinforcement hub in both cases. However, the flange did not fail in this location. The location of failure experienced different service conditions compared to the area above the reinforcement hub. While the amount of stress it sustained was lower, the spool was constantly exposed to hydrochloric acid during service. The presence of chemical attack is assumed in the application of f_{sp} in Equation (2) for the RSF calculations for the spool. For the area near the bolt, the true value of f_{sp} is likely higher which explains the absence of cracking around that area.

The stress concentration at the spool to hub transition in the model also reveals that the flange reinforcement hub is not sufficiently long to accommodate for the bending moment at the flange. The attenuation of the bending moment through the length of the reinforcement hub using Timoshenko's method highlights that there is still localized bending moment remaining and it has not yet decayed at the end of the hub for both design and operating conditions [15]. This behaviour is reflected in the determined RSF value. ASME NM.2 mandates that the hub length is equal to or greater than three times the flange thickness which aids to prevent this issue [12]. From Table 2, the reinforcement hub length for the piping stub was only 26 mm (1.0 in) and the flange thickness was 50 mm (2.0 in), and as such, the residual bending moment created bending in the thin wall of the pipe.

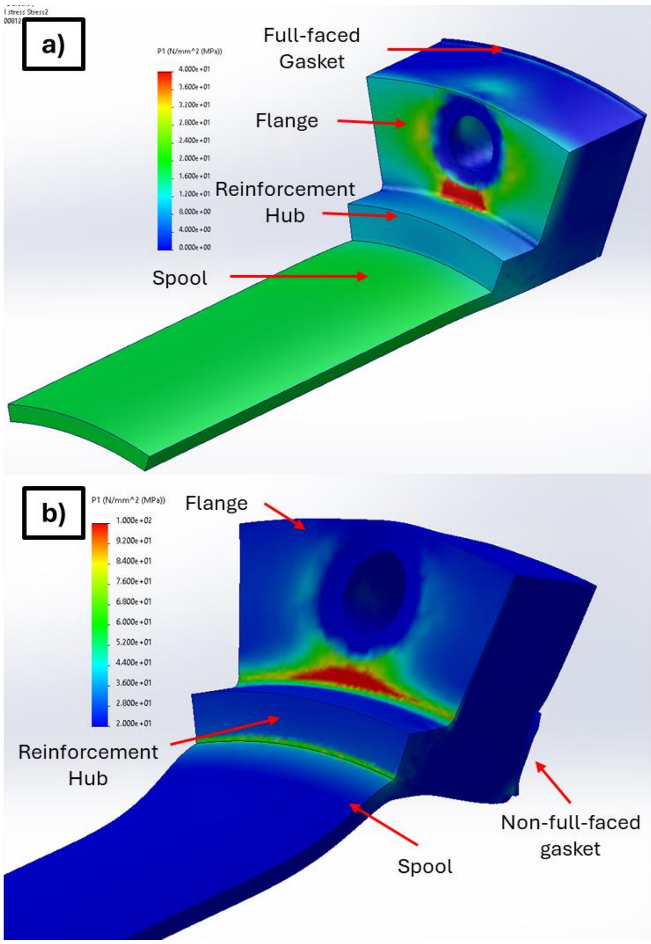

FIGURE 7: SOLIDWORKS MODEL OF THE PIPING STUB FOR A) DESIGN AND B) OPERATING CONDITIONS.

High bolt loads, in addition to the improper flange connection and insufficient reinforcement hub length, imparted a bending moment on the spool for which it was not designed to handle. The bending moment introduced by in-service configuration of the stub resulted in sustained stresses in a spool already undergoing chemical attack, leading to the weakening and ultimate failure of the FRP. Notably, the spool was able to withstand these operating conditions for more than twenty years. However, at the end of its service life, the determined RSF of the spool ultimately did not meet RSF_{FRPa}, showing that the spool would have been deemed not Fit for Service had it been inspected and assessed to WRC601 procedures prior to failure. The application of RSF_{FRPa} as a means to determine FFS in this case would have provided a conservative end of life with a reasonable margin to allow repair.

4. CONCLUSION

The allowable RSF outlined by WRC601 is a conservative value that allows inspectors and engineers to determine objective FFS of pressure equipment made from FRP in accordance with the principles of API 579-1/ASME FFS-1 International Fitness For Service Code [3] without any destructive testing. In both practical cases investigated in this study, the RSF values were similar and the criterion for FFS status was upheld. These two FRP inspections using UAX demonstrate that the value of 0.125 provides conservative, realistic, and practical limits for pressure equipment made from FRP.

REFERENCES

[1] G. Clarkson, Assessment of Existing Fiber Reinforced Polymer Equipment for Structural Damage, WRC Bulletin 601, 4th Edition, New York, NY: Welding Research Council, Inc., 2025.

[2] ASTM, "ASTM C 581, Standard Practice for Determining Chemical Resistance of Thermosetting Resins Used in Glass-Fiber-Reinforced Structures Intended for Liquid Service," ASTM, Conshohocken, 2001.

[3] API & ASME, International Fitness-For-Service, Code Desgnation API 579-1/ASME FFS-1, Washington: API Publishing Services, 2021.

[4] ASTM, ASTM E1118/E1118M-16 Standard Practice for Acoustic Examination of Reinforced Thermosetting Resin Pipe (RTRP), Conshohocken: ASTM, 2020.

[5] ASTM, ASTM E1067/E1067M-25 Standard Practice for Acoustic Emission Examination of Fiberglass Reinforced Plastic Resin (FRP) Tanks/Vessels, Conshohocken: ASTM, 2025.

[6] ASME, BPVC.V - BPVC Section V-Nondestructive Examination, New York, NY: ASME, 2025.

[7] ASTM, "ASTM E1495: Standard Guide for Acousto-Ultrasonic Assessment of Composites, Laminates, and Bonded Joints," ASTM International, West Conshocken, Pa, 2002.

[8] ASTM, "ASTM E1736: Standard Practice for Acousto-Ultrasonic Assessment of Filament-Wound Pressure Vessels," ASTM International, West Conshocken, Pa, 2010.

[9] ASTM, "C1332 Standard Practice for Measurement of Ultrasonic Attenuation Coefficients of Advanced Ceramics by Pulse-Echo Contact Technique," ASTM International, West Conschoken, Pa, 2018.

[10] ASTM, D3299-18 Standard Specification for Filament-Wound-Glass-Fiber-Reinforced Thermoset Resin Corrosion-Resistant Tanks, Conshohocken: ASTM, 2018.

[11] ASME, B31.3 - Process Piping, New York, NY: ASME, 2024.

[12] ASME, NM.2 - Glass-Fiber-Reinforced-Thermosetting-Resin Piping Systems, New York, NY: ASME, 2022.

[13] ASME, "ASME BPVC.X - BPVC Section X-Fiber-Reinforced Plastic Pressure Vessels," ASME, New York, NY, 2025.

[14] ASME, BPVC.VIII.1 - BPVC Section VIII-Rules for Construction of Pressure Vessels Division 1, New York, NY: ASME, 2023.

[15] S. P. Timoshenko and S. Woinowsky-Krieger, Theory of Plates and Shells, New York, NY: McGraw-Hill, 1959.

[16] ASME, NM3.3 - Nonmetallic Materials, Part 3 - Properties, 2022.

[17] US National Bureau of Standards, *Custom Contact-Molded Reinforced -Polyester Chemical-Resistant Process Equipment,* Springfield, VA: U.S. Department of Commerce, 1969.