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Using Ultrasonic Technique to Determine Fitness for Service of FRP Equipment for Chemical Handling Applications

Pradip Khaladkar
PECT Consulting
Hockessin,
Delaware
USA

Geoffrey Clarkson
UTComp Inc.
Cambridge, ON, N1R 8C8
Canada

ABSTRACT

Fiberglass reinforced plastic materials are well suited to a wide variety of chemical handling equipment where resistance to corrosion is required. A significant impediment to adoption of these materials for many suitable applications lies with the inability to do a fitness for service determination after the equipment and piping have been in service. This is largely due to the lack of effective non-destructive and non-intrusive techniques for plastic materials. This paper presents a case study of a fiberglass reinforced plastic scrubber which was evaluated with a novel ultrasonic technique followed by a destructive evaluation for retained mechanical properties and corrosion barrier condition. When compared, the results showed good correlation. Although the FRP unit was already discarded this study indicated that significant life had still remained.

Key words: Non-destructive testing, FRP, corrosion barrier, fitness for service

INTRODUCTION

Many chemical processing facilities use fiberglass reinforced plastic (FRP) to contain corrosive liquids and gases. Current practice in the chemical industry is to base the useful life of FRP on the condition of the surface and near-surface that is exposed to the corrosive conditions. This part of FRP structure is known as the corrosion barrier, and is constructed to act as a barrier that reduces corrosion and chemical attack of the FRP that supports the structural and pressure loads required. In general, structural contribution from the corrosion barrier is not considered in the design of FRP vessels and pipe.

Current practice in the chemical processing industry is to base the useful life of FRP equipment on the condition of the corrosion barrier. Once the corrosion barrier is compromised, the FRP carrying the structural loads can degrade rapidly, sometimes leading to catastrophic failure. Traditional assessment of the corrosion barrier allows some measurements and calculations of corrosion and oxidation rates and prediction of maintenance needs for the corrosion barrier. With the use of best practices and skilled inspectors, reliability gains can result. However, there are limitations of this visual inspection process: confined space entry is almost always required, equipment must usually be evaluated during outages, most piping cannot be inspected, limited evaluation can be made of the structural condition of FRP and skilled inspectors are relatively rare. While these conventional inspections are normally non-destructive, they are not non-intrusive. Because of the many limitations, it is not always possible to determine corrosion barrier damage in a timely and efficient manner.

In some cases, corrosion barrier damage is discovered only at a late stage, resulting in damage to the structural thickness and leading to emergency responses to find solutions and maintain facility operations. These responses normally involve additional intrusive and destructive testing and sometimes total replacement.

This case investigates whether a novel non-destructive and non-intrusive ultrasonic technique can be used to provide timely information about the condition of FRP equipment in corrosion service.

Equipment Configuration and Description

The FRP equipment used for this investigation was a vent scrubber at a facility of a large chemical company. The scrubber was used to neutralize hazardous gas with sodium hydroxide solution in a countercurrent flow. The configuration is shown in Figure 1.

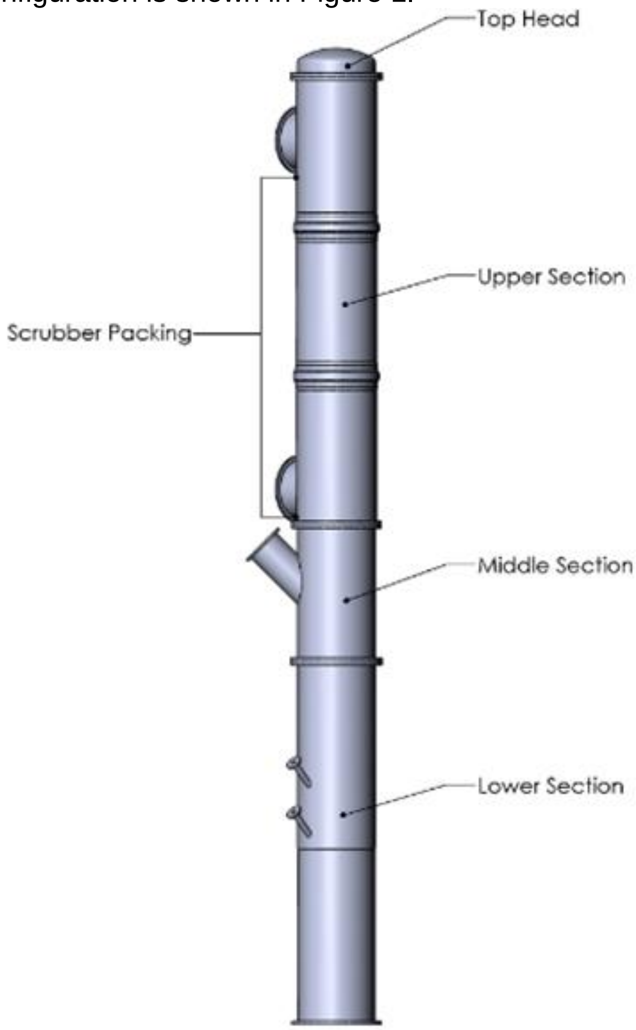


Figure 1: Equipment Configuration

The original scrubber had been built and installed in 1985. In 1995, all sections were replaced. In 2002, the lower section was replaced. In 2015, all sections of the scrubber were replaced because the structural integrity was suspected to be compromised based on visual inspection of the corrosion barrier. The scrubber that was removed in 2015 is the subject of this investigation, since it was no longer in service and could be made available for comparison of non-destructive and destructive evaluation.

All sections of the scrubber from 1985 to 2002 were manufactured by the same manufacturer. The lay-up method was contact molded, known as hand lay-up. The corrosion barrier thickness was about 5.4mm. The resin was a Bisphenol-A epoxy vinyl ester. The corrosion barrier was cured using BPO/DMA and post-curing, where the structural FRP used MEKP cure. Full details on the lamination are below.

History of Ultrasonic Testing of FRP

In the early 1960's, use of ultrasonic testing (UT) was already showing reliable results for finding flaws in metallic structures. One of the desirable attributes of this technique is that reliable data could be generated if only one side of the material under investigation was accessible. This meant that in addition to finding flaws or defects, the same techniques could be used to produce thickness records of reasonable accuracy. At the same time, use of composite materials such as glass reinforced thermoset plastics was being explored for a number of structural and corrosion-resistant applications. Starting in the mid 1960's, researchers started to examine uses of ultrasound with these fiber-reinforced composite materials.

Vary[1] applied ultrasonic pulses to composites and received the responses using acousto-ultrasonic devices, thus mixing the principles of ultrasound with acoustic emission testing. This process is known as "acousto-ultrasonic" because the forces applied to the specimen are from ultrasonic pulses, whereas for acoustic emission, the forces applied to the composite are from mechanical loads applied, such as pressures and weights. In both cases, the responses are received in real time by acoustical equipment. This work showed correlation between the attenuation of the signal transmitted through the full thickness of a laminate – across its layers - and its tensile strength parallel to its layers. This technique is the subject of two American Society for Testing and Materials (ASTM) standards – ASTM E 1495 Standard Guide for Acousto-Ultrasonic Assessment of Composite, Laminates and Bonded Joints[2] (ASTM E 1495) and ASTM E 1736 Standard Practice for Acousto-Ultrasonic Assessment of Filament Wound Pressure Vessels[3] (ASTM E 1736).

Several researchers[1,4,5] have reported experimental results showing good correlation between the elastic modulus of FRP and acousto-ultrasonic results. This includes correlation of changes in strength that has occurred from applied stresses and chemical permeation with changes in ultrasonic response of the FRP. These early researchers have successfully shown that acousto-ultrasonic methods can be used to determine changes in condition of composite laminates. With the appropriate criteria, this information can be used to determine whether a composite laminate is suitable for the loads to be applied in service conditions.

EXPERIMENTAL PROCEDURE

Non-Destructive Ultrasonic Assessment

The scrubber was provided in a location where it could be inspected using contact of an ultrasonic transducer on the outside surface. All openings were covered, thus allowing a non-intrusive inspection to be simulated. During the ultrasonic inspection, the inspector had no access to the inside of the scrubber. This ensured that reports from the ultrasonic inspection did not contain any fore-knowledge about the condition of the corrosion barrier.

The Ultrasonic Assessment of the fiberglass reinforced plastic (FRP) in the scrubber used the equipment and procedure outlined below:

1. The transducer was a 500kHz complete with crosslinked rubber delay line.
2. Conventional Ultrasonic Flaw Detector was used.
3. Complete A-Scan image data and instrument settings were saved for each reading taken. The readings were:

    a. Only the transducer with delay line.
    b. Readings with the transducer delay line coupled to the surface of the FRP, generally spaced in a pattern.
    c. Only the transducer with delay line.
4. All readings saved were exported from the Flaw Detector into a computer.
5. The exported data was post-processed in a computer program, where every reading was analyzed. The two transducer-only readings were used to:
    a. determine the effect of any temperature changes that may have occurred while the readings were taken, and
    b. provide reference signal to determine attenuation.

The results of the processed readings were then saved in a computer file.

The above is documented in a written procedure that has been reviewed by ASME[i] Level III Ultrasonic Inspectors.

Description of ultrasonic inspections and the locations of cutouts removed for verification is shown in Figure 2 along with details of inspection locations.

Comparative Visual and Destructive Assessment

After the non-destructive readings were taken, portions of the FRP shell were removed for comparative evaluation. Figure 3 shows all of the cutouts removed from the vessel along with their locations. Cutouts QT1, FM3 and QM2 were not used for quantitative property verification because they were too small or did not have uniform thickness. The section of some of these samples were examined for verification of the condition of the corrosion barrier as reported from the ultrasonic analysis. This was the first time that the inspection contractor witnessed the internal condition of the FRP.

[i] American Society of Mechanical Engineers, New York, NY.

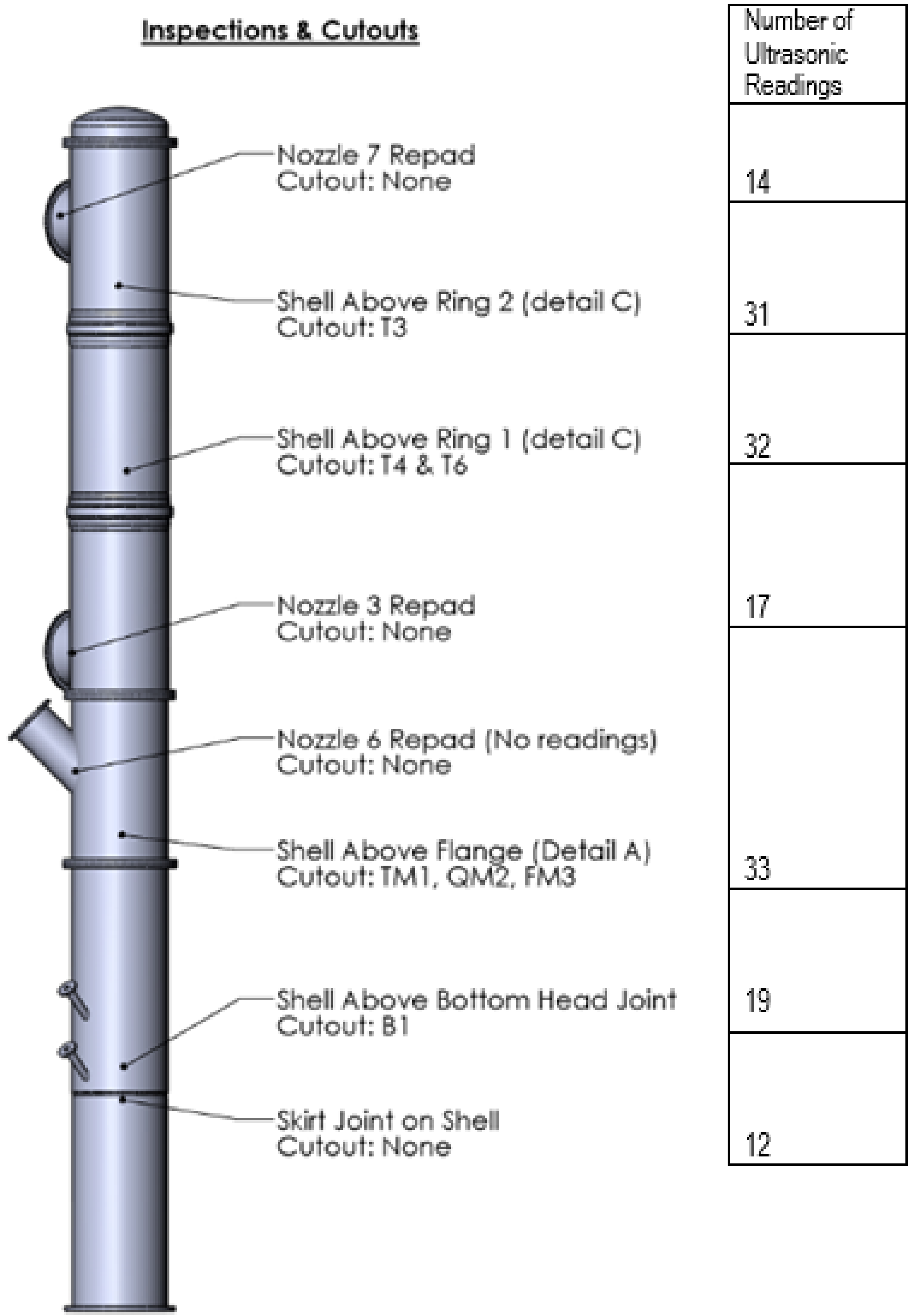


Figure 2: Inspections

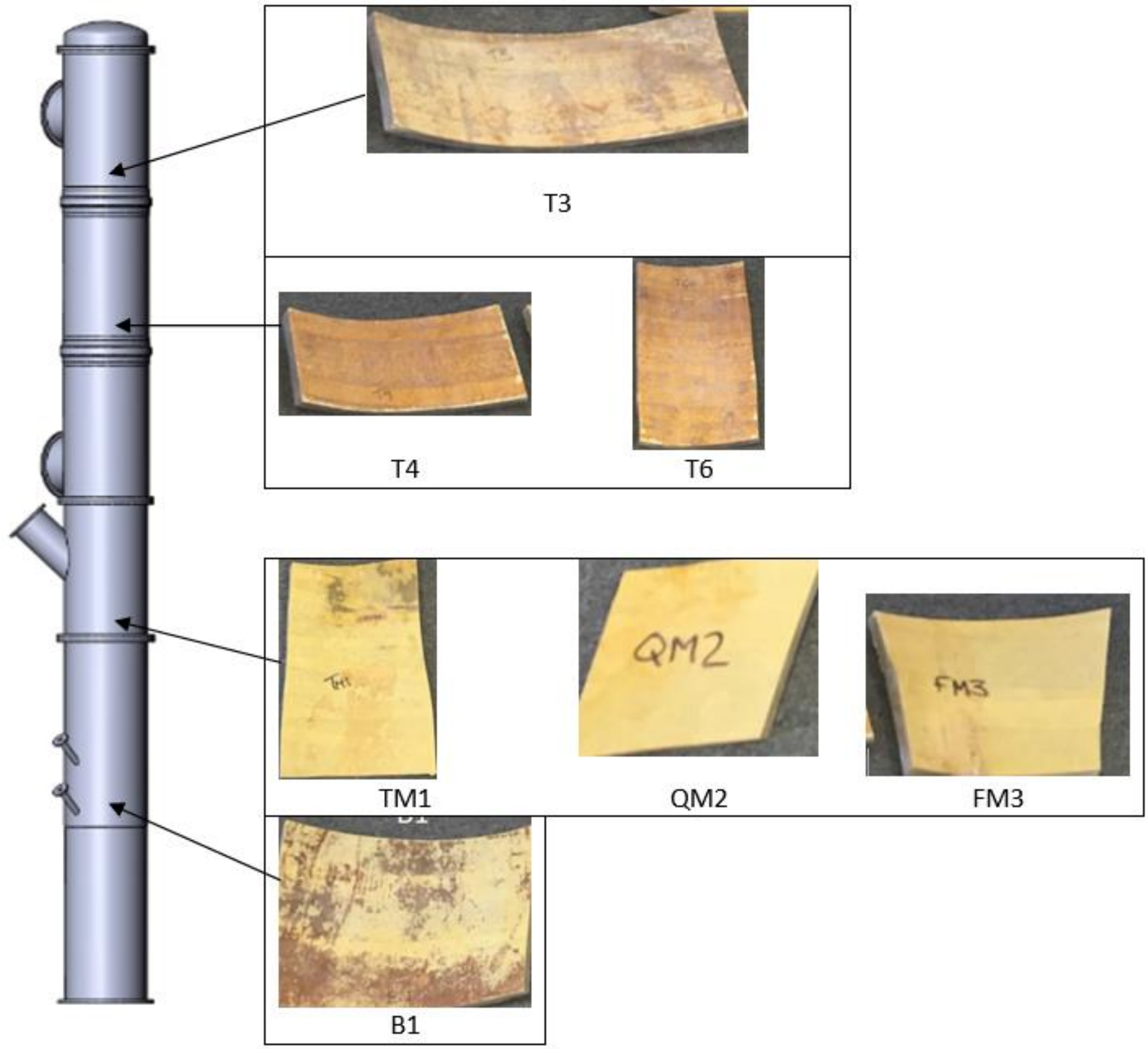


Figure 3: Cutouts from Scrubber

RESULTS

Non-Destructive Analysis Results

From the ultrasonic readings, results were obtained regarding both damage to the inner surface of the FRP from chemical reactions in the scrubber and the current structural condition of the FRP.

The data from the inspection was evaluated following the methods described in (6) to determine the structural capacity of the FRP.

Structural capacity is expressed as Percentage of Design Stiffness (PDS) as shown in equation 1.

$$PDS = \frac{Current\ Flexural\ Modulus}{Theoretical\ Modulus} \quad (1)$$

The Critical PDS is the value of Percentage of Design Stiffness which is considered in this analysis to be the minimum allowable value for equipment operation.

Calculation of Critical PDS is given in equation 2. For conservative results, the nominal design factor used for new design is taken to be 10. This is consistent with many standards for FRP vessel design.

$$Critical\ PDS = \frac{2}{Max(Design\ Factor, 10)} \times 100\% \quad (2)$$

In addition to the structural assessment, the ultrasonic readings were evaluated for features that indicate the condition of the inner, process side, surface.
The results of the non-intrusive ultrasonic tests are given in Table 1.

Table 1: Non-intrusive Non-destructive (UT) Structural Results

Section	Average Thickness (mm)	Section Average PDS
Nozzle 7 Repad	43.6[ii]	66%
Shell Above Ring 2 (Detail C)	19.8[iii]	72%
Shell Above Ring 1 (Detail C)	19.8	69%
Nozzle 3 Repad	41.5	93%
Shell Above Flange (Detail D)	27.8[iv]	66%
Shell Above Flange (Detail A)	19.8	87%
Shell above bottom head joint	16.0	72%
Bottom head joint	33.8	100%

The PDS values in Table 1 are converted to predicted results from destructive flexural testing below.

Laminate Physical Properties

The original laminate physical properties for this vessel are no longer available from the manufacturer. Lamination sequences are provided on the original drawing for the shells and heads. These lamination sequences correspond to the thicknesses provided on the drawing. All shell sections are shown to have nominal thickness of 0.55 inch (14mm) with the following lamination sequences chosen by the manufacturer. The sequence NNME CCME comprises the corrosion barrier in this case.

NNME CCME MRMRE MRMM

Where:
N = Polyester veil
C = C-glass veil
M = 460 g/m^2 Chopped Strand Mat (CSM)
E = 460 g/m^2 CSM (exotherm stop)
R = 812 g/m^2 Woven Roving (WR)
Resin: Derakane 411-35

For this lamination sequence, the hoop flexural modulus and axial tensile modulus values have been determined using Classical Lamination Theory as:

Flexural Modulus – Hoop (1,375 ksi) (9.47 GPa)
Tensile Modulus – Hoop and Axial 1,573 ksi (10.84 GPa)

The lamination sequence corresponds with the lamination sequence given in the drawing. The thickness of the shell sections as determined from ultrasound appears to be greater than the drawing value. This may be due to addition of layers. This is expected to have small effect on the modulus values.

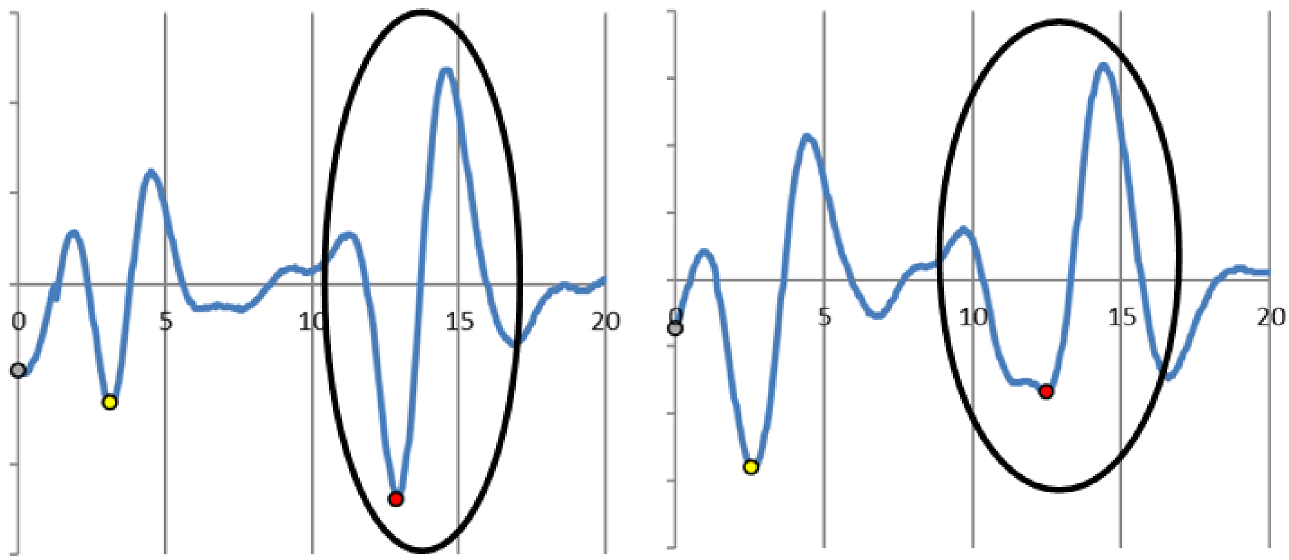
[ii] Total repad and joint thickness is based on expected sonic velocity and transit time.
[iii] Thickness from drawing provides sonic velocity within nominal limits for all readings with 19.8mm thickness.
[iv] Thickness is based on transit time and expected velocity from database. Near the flange, this probably includes reinforcement.

Five (5) cutouts were selected for comparative destructive testing according to ASTM D790[7] and predictions of the test results were made for those locations. The predictions are listed in Table 2.

Table 2: Predicted Results for Destructive Testing from UT

Section	Average PDS	Hoop Flexural Modulus (GPa/ksi)	Axial Flexural Modulus (ksi)
Shell Above Ring 2 (Detail C)	72%	6.82 / 990	7.80 / 1,133
Shell Above Ring 1 (Detail C)	69%	6.54 / 949	7.48 / 1,085
Shell Above Flange (Detail D)	66%	6.25 / 908	7.15 / 1,038
Shell Above Flange (Detail A)	87%	8.24 / 1,196	9.43 / 1,368
Shell above bottom head joint	72%	6.82 / 990	7.80 / 1,133

Corrosion Barrier Assessment
Corrosion barrier assessment was completed by evaluating features within the opposite surface reflection of the ultrasonic reading. Figure 4 shows a typical comparison taken from different locations in the Shell Above Ring 1 (Detail C, Cutout T4). Common features used to determine if damage has occurred are the width of the main reflection lobe (circled area) and the presence of undulations in the reflection.



a) Undamaged Corrosion Barrier

b) Damaged Corrosion Barrier – Damage depth 1.75mm

Figure 4: Typical Corrosion Barrier Analysis

The results of the ultrasonic assessment of the corrosion barrier are listed in Table 3.

Table 3: Ultrasonic Corrosion Barrier Assessment

Section	Corrosion Barrier Assessment
Nozzle 7 Repad	Some damage detected in 50% of readings
Shell Above Ring 2 (Detail C)	Some damage detected in 16% of readings
Shell Above Ring 1 (Detail C)	Minor damage detected in 23% of readings
Nozzle 3 Repad	No damage detected
Shell Above Flange (Detail D)	No damage detected
Shell Above Flange (Detail A)	No damage detected
Shell above bottom head joint	No damage detected
Bottom head joint	No damage detected

In table 3, the average depth of corrosion barrier damage detected for the shell sections above rings 1 and 2 was 1.25mm. Based on the shape of the reflected ultrasonic signal, the type of damage was assessed to be caused by oxidation of the resin.

Destructive Analysis

The destructive testing was completed by a third party, a reputable fabricator with no connection to the scrubber. The test method chosen was "Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials", designation ASTM D 790. From this, the flexural modulus of the test specimens was determined.

Comparison of the destructive results with the predicted values is provided in Table 4. In table 4, the percentage difference is determined according to equation (3).

$$\%Difference = \frac{Flexural\ Modulus\ Prediction - D\ 790\ Result}{D\ 790\ Result} \qquad (3)$$

Table 4: Comparison of Predicted with Destructive Flexural Modulus

Location	Cutout	Predicted Value by UT(GPa/ksi)	Test Value from D790[2] (GPa/ksi)	% Difference
Shell Above Ring 2 (Detail C)	T3	6.82 / 990	6.53 / 948	4%
Shell Above Ring 1 (Detail C)	T4	6.54 / 949	5.89 / 855	11%
	T6	6.25 / 908	6.70 / 973	-2%
Shell Above Flange (Detail D)	T2	8.24 / 1,196	6.70 / 973	-7%
Shell Above Flange (Detail A)	TM1	6.82 / 990	7.21 / 1,047	14%
Shell above bottom head joint	B1	6.82 / 990	7.02 / 1,019	-3%

Another illustration of the results is given by the chart in Figure 5. This chart also shows the range of the individual flexural modulus results from the D 790 test.

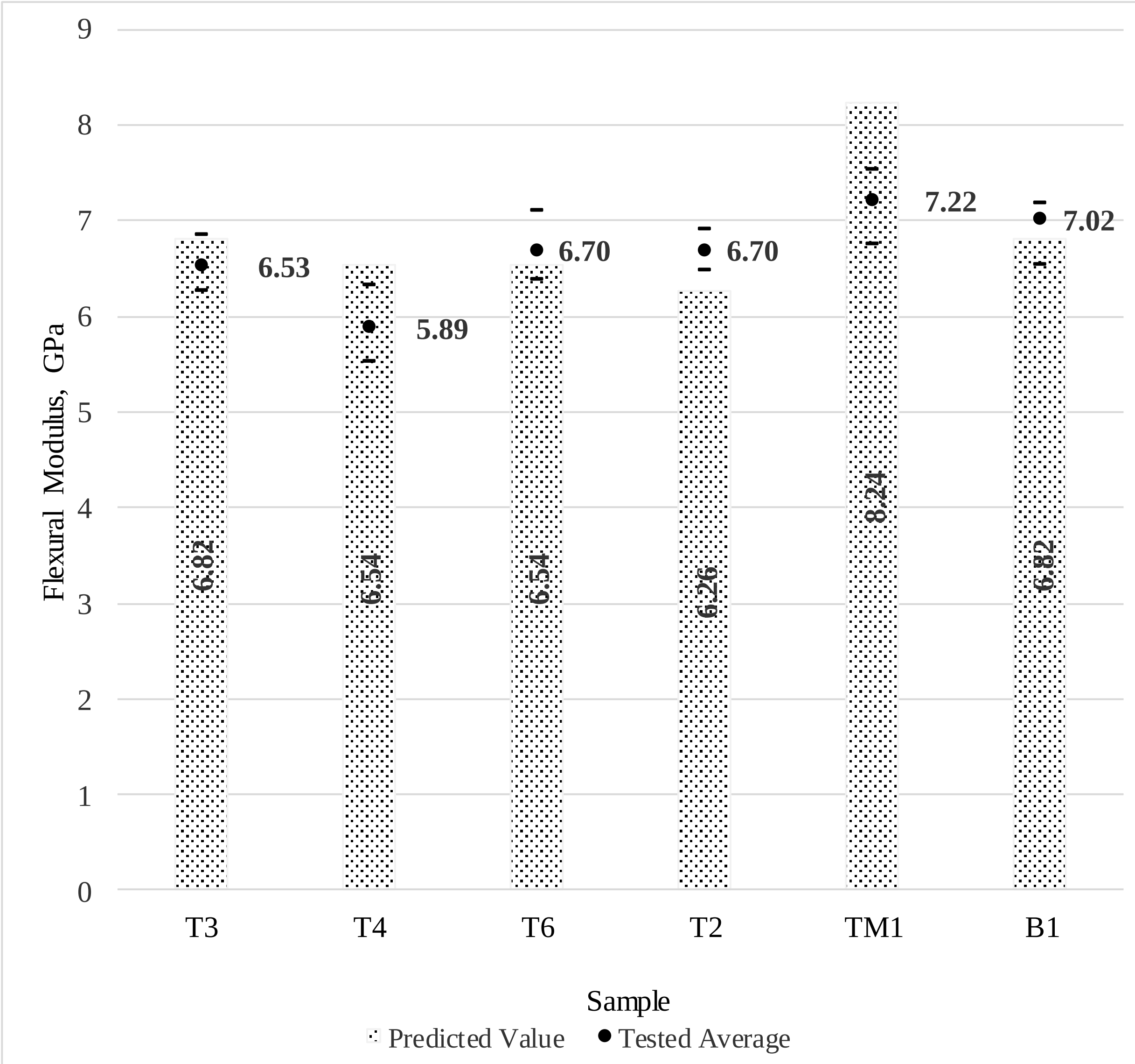
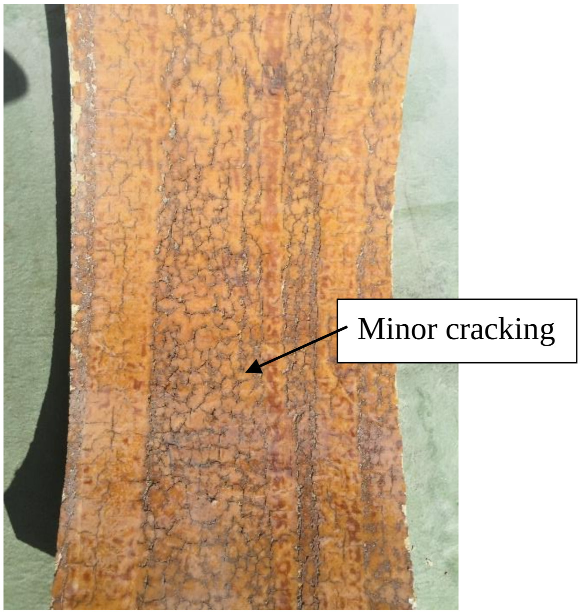


Figure 5: Chart of Stiffness Results Comparison

Several of the cutouts were examined to quantify the damage to the corrosion barrier. Figure 6 shows the T4 cutout. In Figure 6a, the inner surface of the corrosion barrier shows the damage and loss of material. Figure 6b shows the edge of the cutout.

Note that the ultrasonic assessment determined that the average depth of damage to this section of the corrosion barrier was 1.25mm. Evaluation of the cutout confirmed the ultrasonic results where the damage depth to the corrosion barrier was measured in the lab to correspond to the results in Table 3. Note also that the remainder of the shell thickness in Figure 6b does not show any signs of damage.



a) Inner Surface of T4

b) Edge of T4 Cutout

Figure 6: Corrosion Barrier

Remaining Service Life Prediction

The principal output of the ultrasonic analysis PDS. From the PDS, the following calculations are made to provide a prediction of the remaining time when the FRP will have sufficient structural capacity.

The PDS Rate of Change (ΔPDS) is the average linear rate at which PDS is changing for the equipment:

$$\Delta PDS = \frac{Starting\ PDS - Current\ PDS}{Starting\ Year - Current\ Year} \qquad (3)$$

For this scrubber, this was the first evaluation using this method and no previous data was available. When this occurs, it is conservative to assume that the new FRP had 100% of its theoretical strength when new. Also, note from above that the upper sections and lower section were different ages, therefore different ΔPDS values will exist.

The Remaining Service Life (RSL) is the number of years until the PDS of the section is predicted to be at Critical PDS. The calculation to be made is:

$$Remaining\ Service\ Life = \frac{Critical\ PDS - Current\ PDS}{\Delta PDS} \qquad (4)$$

This calculation is consistent with calculations required by API 653[8] when PDS is substituted for thickness.

The results of the calculations are given in Table 5.

Table 5. Remaining Service Life Calculation

Scrubber Section	Current Minimum PDS	Remaining Service Life (yr)
Bottom Section	72%	25
Upper Shell and Head	66%	27

This is illustrated graphically in Figure 7.

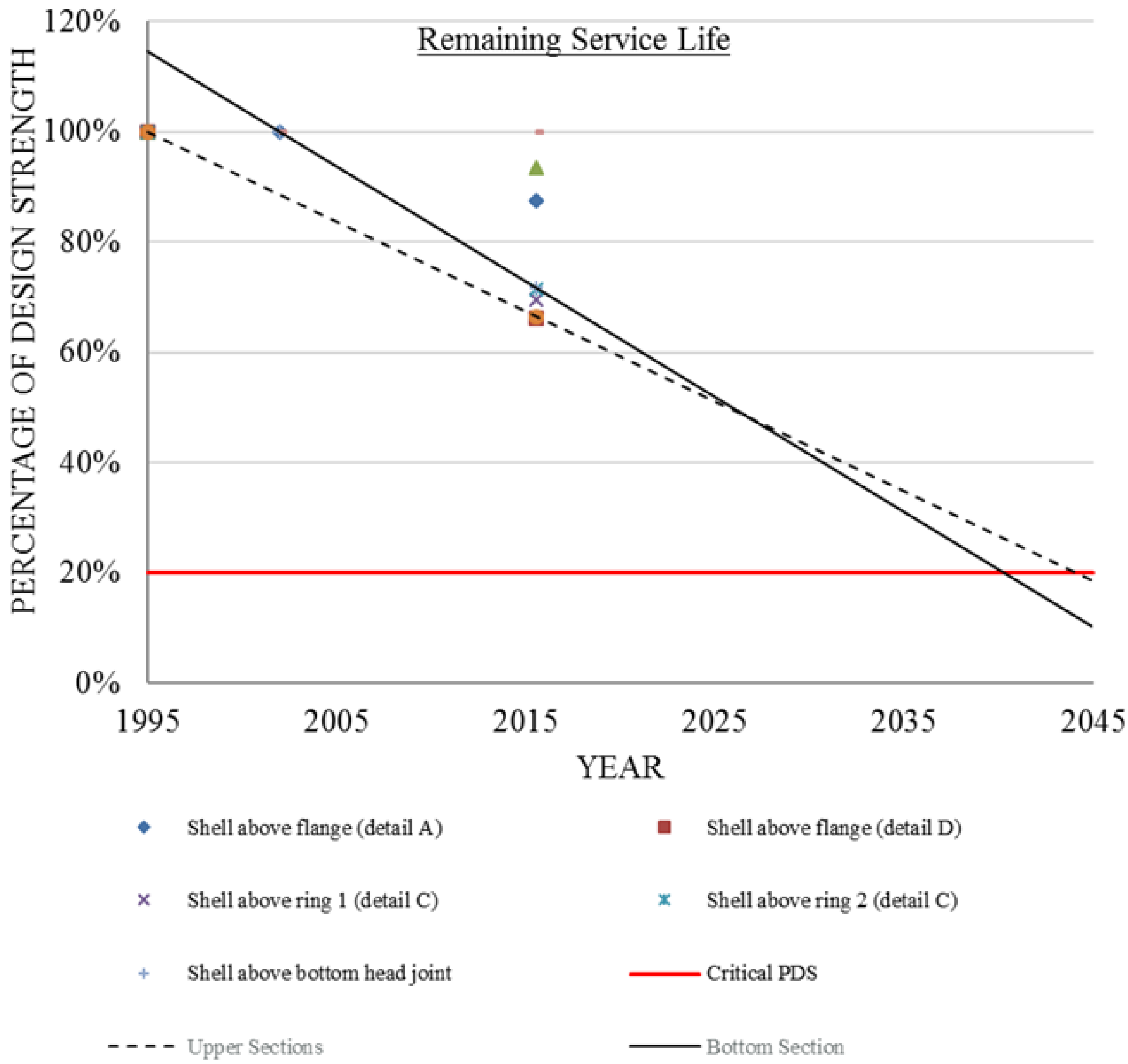


Figure 7: Chart Showing Remaining Service Life

Remaining service life could also be determined on the basis of the corrosion barrier damage detected in this case using the damage depth and criteria for end of corrosion barrier service life.

CONCLUSIONS

The results provided a good match between information provided by the UT readings and the actual retained mechanical properties of the cutouts. The examination of the cutouts also indicated minimal damage to the corrosion barrier thereby suggesting a significant remaining life which this study also predicted. Fitness for service of FRP equipment in chemical handling applications is usually done by the condition of the corrosion barrier. However, plant operations are often confronted by situations where the structural integrity of the equipment is in question due to or regardless of the condition of the corrosion barrier. In such situations this UT technique could be helpful as evidenced by this study. More such studies are required to verify and fine-tune the predictability of this technique.

ACKNOWLEDGEMENTS

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