ANALYSIS AND EVALUATION OF THE STRUCTURAL HEALTH OF PRESSURE VESSELS WITH GENERAL CORROSION APPLYING API 579

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Abstract. *This paper presents the analysis of the structural health of pressure vessels with a region of general metal loss resulting from corrosion using the API 579 fitness for service comparing with finite element method (FEM) for determine the reduced maximum allowable working pressure (MAWP). The Fitness-for-Service assessments are quantitative engineering evaluations which are performed to demonstrate the structural integrity of an in-service component containing a flaw or damage. The objective is to analyze and evaluate the values of reduced MAWP pressure using the API 579 and MEF solutions to cases of thickness profiles available by ultrasound inspection and still provide a method for modeling of the damaged region. The activity of the fitness for service for pressurized components depends on the answers to several questions. We can cite as examples the knowledge of bounds for region with metal loss due to corrosion, the interval between inspections recommended for equipment that operates subject to failures, determining the failure probability of equipment, definition of material properties for assessment integrity of a structure, project evaluation and materials used in equipment subject to low temperatures (brittle fracture) and safety factors appropriate for an equipment with high operational risk and cumulative damage. Calculation methods are provided to rerate the component if the acceptance criteria are not satisfied. The procedures can be used to qualify a component for continued operation or rerating. The API 579 has criteria for assessment of damages are defined by the allowable stress and remaining strength factor (RSF). The allowable stress criterion is based on the comparison of stresses acting with permissible values provided by the code of original equipment manufacturing. This criterion has limited application in damage assessment of components with the difficulty of establishing the level of stresses acting. The remaining strength factor criterion is used to define the acceptability of a component for continuous operation. From the evolution of pressure vessel with general metal loss using API 579 makes a comparison with the numerical analysis with NX 7.0 finite element software for providing work margin and safety for operation and inspection. The analysis was developed with data from a pressure vessel that operates with 400 psig of pressure, 350°F of temperature, internal diameter of 80 in, nominal thickness 1,25 in, for material SA 516 grade 70 that has an general metal loss area by corrosion in outer surface collected by ultrasonic inspection. The metal loss area was modeled in the NX 7.0 FEM software to compare with the API 579 procedures for calculate the minimum required thickness, length for thickness averaging, determine if the component is acceptable for continued operation and determine the reduced maximum allowable working pressure (MAWP).*

Keywords*: structural health, pressure vessel, numeric analysis, fitness for service, corrosion.*

1. INTRODUCTION

First presents an introduction to pressure vessels, ASME code addressing that regulates the manufacture, testing and design. The following is a review about Fitness for Service API 579 for general metal loss in order to establish a connection to resistance determined by pressure vessel design codes and fitness for service API 579.

Pressure vessels are devices used in process industries, oil refineries, petrochemical, food and pharmaceutical industries. These equipments must be designed and constructed to avoid of the damages causes that are: excessive elastic deformation, including elastic instability, excessive plastic deformation, including plastic instability, high local stresses, and high temperature creep, brittle fracture at low temperature, fatigue and corrosion.

As a result of several serious accidents occurred mainly in the United States of America (USA) in the early twentieth century, were created working groups to define certain criteria of design, fabrication and inspection of pressure vessels and thus emerged the design codes.

The first U.S. Code, for pressure vessels, was published by ASME (*American Society of Mechanical Engineers*) in 1925, entitled "Rules for Construction of Pressure Vessels, Section VIII, 1925 Edition. All codes are intended to establish rules for safe design and manufacture, nondestructive testing, and materials applicable to allowable stress. Periodically, the codes are subject to revisions and new editions to incorporate new topics and changes resulting from technological advancement.

Each code adopts criteria and methodologies, and in Brazil the most used are the American Code ASME Section VIII, Division 1 and Division 2, English and German BS-5500 AD-Merkbläter. There are other important codes such as 3 Division of ASME, French (SNTC / AFNOR - Calcul des appareils the Pression) and Japanese (JIS).

Are presented below the main features of the codes adopted more frequently, referring only the part devoted to mechanical design and greater emphasis on codes ASME Section VIII Division 2 established in 1969 which adopts the criteria and details of design, fabrication, testing and allowable stress tests and not limiting design pressure.

The design criteria adopts classification of strains for most usual loading combinations, fatigue analysis for equipment under loading cyclical conditions, thermal gradients and alternative project-based stress analysis in geometric discontinuities.

The maximum shear stress theory (shear rupture at maximum) is adopted, known as the Tresca Criterion, is fitness for fatigue analysis.

On the walls of pressure vessels there are stress that can be called membrane stress and bending stress, and even tangential stresses and longitudinal stresses depend on the ratio between wall thickness and internal radius from the internal pressure.

This paper presents an analysis and evaluation of pressure vessel using the API 579. From the procedures defined by the standard, a numerical analysis of pressure vessel with the corroded region to determine the reduced maximum allowable working pressure (*MAWP*).

The minimum required wall thickness, *MAWP* and membrane stress for common pressure components are required for many of the Level 1 and Level 2 fitness-for-service assessments. These parameters may be computed using the appropriate equations from the construction code. The equations are based on the following publications: the ASME B&PV Code; Section VIII, Division 1; WRC 406 and ASME B&PV Code Case 2286; and ASME B31.3. The equations are presented in an organized fashion to facilitate use, and are adjusted for metal loss and future corrosion allowance.

The numerical analysis can be an important tool to show the procedures of the standards are correct, or even work as a control parameter for the equipment lifetime.

2. FITNESS FOR SERVICE

In Fitness for Service assessment thickness data are required on the component where metal loss has occurred to evaluate general metal loss. Computation of the minimum wall thickness, *MAWP* and membrane stress for existing equipment typically requires judgment on the part of the user to determine factors and parameters which may significantly affect the final results (e.g. code revisions, determination of allowable stresses for in service components, weld joint efficiency in corroded regions) (API 579, 2000).

Thickness readings which are required to determine the metal loss on a component are usually made using straight beam ultrasonic thickness examination (UT). This method can provide high accuracy and can be used for point thickness readings and in obtaining thickness profiles (continuous line scans or area scans can also be used to obtain thickness profiles). The limitations of UT are associated with uneven surfaces and access.

2.1. Fitness for Service Analysis to Pressure Vessel

The equipment analyzed was a pressure vessel made of steel ASTM A516 Grade 70 with longitudinal welded joint for 400 psi of work pressure, 80 inch inside diameter, 1.25 inch of nominal wall thickness, 0.10 inch future corrosion and that presents region with corrosion shown in the figure below. In the Fig. 1 shows the equipment with grid of inspection by ultrasound tests in the region corroded.

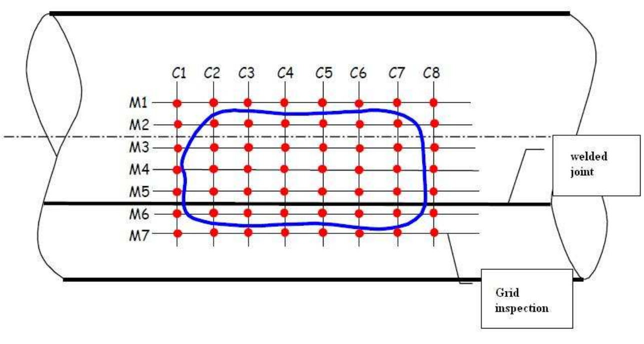


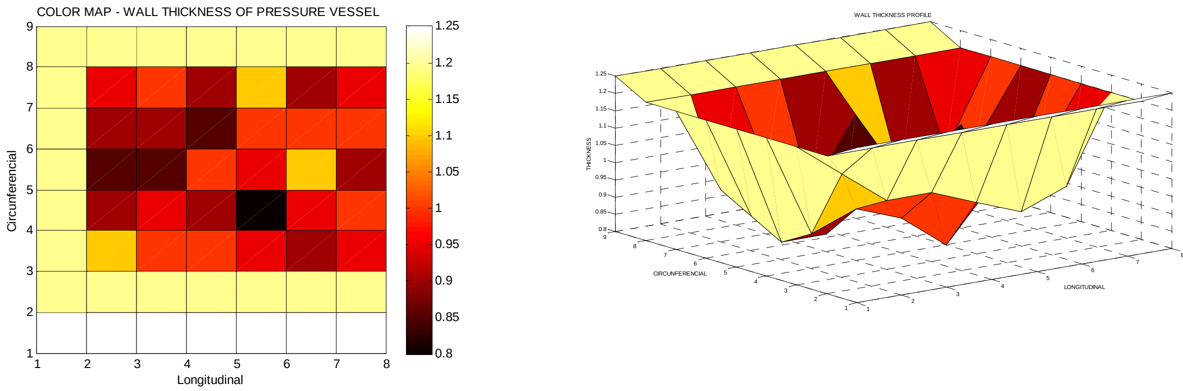
Figure 1. The grid inspection in the region corroded.

After ultrasound inspection, the wall thicknesses profile of region with metal loss was collected. Each point is a longitudinal distance of 2.5 inch. The inspection grid was created around the region with corrosion (blue line). The Table 1 shows the values for the wall thickness by ultrasound tests in the longitudinal and circunferencial inspection planes.

Table 1. Wall thickness for the longitudinal and circunferencial inspection planes.

Inspection plane (in)	C1	C2	C3	C4	C5	C6	C7	C8
M1	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
M2	1.20	1.10	1.00	1.00	0.95	0.90	0.95	1.20
M3	1.20	0.90	0.95	0.90	0.80	0.95	1.00	1.20
M4	1.20	0.85	0.85	1.00	0.95	1.10	0.90	1.20
M5	1.20	0.90	0.90	0.85	1.00	1.00	1.00	1.20
M6	1.20	0.95	1.00	0.90	1.10	0.90	0.95	1.20
M7	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20

The assessment procedure to be used in an evaluation is dependent on the type of thickness data are available, see the Fig. 2, the characteristics of the metal loss (i.e. uniform or local), the minimum required wall thickness, and the degree of conservatism acceptable for the assessment. The profile wall thickness is presented in the Fig. 2.



(a) (b)

Figure 2. Color Map for profile wall thickness of pressure vessel.

The mechanical properties of carbon steel begins to suffer a sharp drop in temperatures above 400°C, but in this case the temperature is about 177°C (350° F), so will not consider changes in steel properties due to temperature (Telles, 1996). Then, by Telles (1996) for low temperatures, the allowable stress is 137.70 MPa or 19.90 kpsi.

The API 579 fitness for service provides some steps that are:

1. Define the minimum thickness required, t_{min}.
2. Profile wall thickness, just provided by ultrasound in the Tab.1;
3. Determine of the average thickness length, L;
   i. Determine the minimum thickness (t_{mm}) and the remaining thickness ratio (R_t);
4. Determine the Critical Thickness Profiles (*CTP's*), in this case find just the longitudinal profile, for ensuring the list below is not necessary to determine the circumferential profile and consequently the dimension *c*.

If point thickness readings are used in the assessment, the assumption of general metal loss should be confirmed. A minimum of 15 thickness readings is recommended unless the level of NDE utilized can be used to confirm that the metal loss is general. In some cases, additional readings may be required based on the size of the component, the construction details utilized, and the nature of the environment resulting in the metal loss. If the Coefficient of Variation (*COV)*, defined as the standard deviation divided by the average, of the thickness readings minus the Future Corrosion Allowance (*FCA*) is greater than 10%, then the use of thickness profiles should be considered for use in the assessment. Then the COV is 0.14 or 14%, thus should be considered the *CTP*.

The *CTP* in each direction is determined by projecting the minimum remaining thickness for each position along all parallel inspection planes onto a common plane. The length of the profile is established by determining the end point locations where the remaining wall thickness is greater than t_{min} in the meridional and circumferential directions. Note that the remaining wall thickness within the bounds of the *CTP* may exceed t_{min}.

In the Fig. 3 shows the Longitudinal Critical Thickness Profile (*CTP*) for the region corroded by fitness for service API 579. Presents the nominal thickness (*t*), the longitudinal *CTP* (green), the critical *CTP* (black) means that the higher profile that the region corroded may have in the future for pressure vessel can operate safely by API 579. The line red shows the minimum thickness.

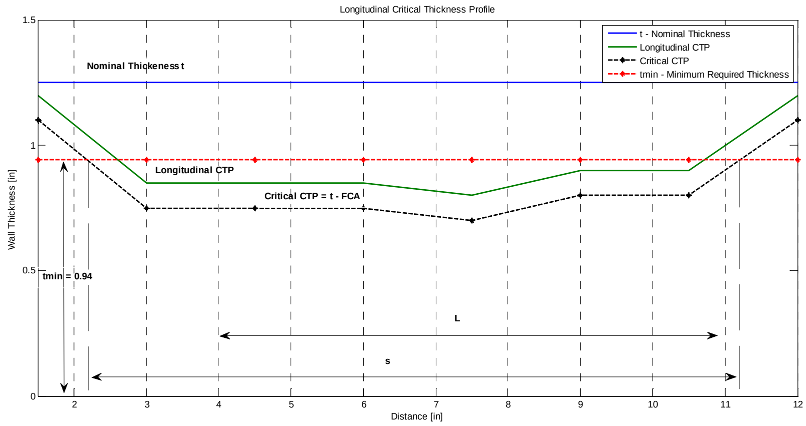


Figure 3. Longitudinal Critical Thickness Profile

From the Fig.3, *s* and *c* are dimensions which define the region of metal loss in the longitudinal and circumferencial directions, respectively. The flow dimension *s* is 14.43 in, and the circumferential CTP does not need to be determined because the minimum required thickness based on the circumferential plane (longitudinal stress) is less than the average measured thickness (see Step 2).

The minimum required thickness (t_{min}) is 0.941 in. From API 579, note that in this case, *c* is not required because the minimum required thickness for the circumferential direction is less than the minimum measured thickness, or

$$(t_{\min}^{L} = 0.47in) < (t_{mm} - FCA = 0.800 - 0.100 = 0.700in) \tag{1}$$

Follows the step 5 and from the step 3 and the Fig. 3, the length for thickness averaging is 10.65 in, thus since $s > L$, this evaluation can be performed by direct averaging the thickness readings that reside within length *L*.

$$t_{am} = t_{am}^{S} = \frac{0.85 + 0.85 + 0.80 + 0.90 + 0.90}{5} = 0.860in \tag{2}$$

Follows the step 6, determine if the component is acceptable for continued operation, thus the next Eq. (3) and Eq. (4) must be true. Thus, the average measured wall thickness should satisfy the following. Alternatively, the *MAWP* calculated based on the thickness should to be equal to or greater than current *MAWP* (Maximum Allowable Working Pressure).

$$t_{am} - FCA \geq t_{\min} \tag{3}$$

$$t_{am} - FCA \geq t_{\min} \Rightarrow 0.860 - 0.100 \geq 0.941 \Rightarrow 0{,}760in \geq 0{,}941in(\,false)$$

The Eq. (3) was false, thus the minimum measured wall thickness should satisfy the following thickness criterion.

$$t_{mm} - FCA \geq \max(0.5 \times t_{\min}, 2.5mm(0{,}1in)) \tag{4}$$

For cylindrical shells the minimum thickness, *MAWP* and membrane stress equations are as follows (see ASME B&PV Code, Section VIII, Division 1, paragraph UG-27). For Circumferential Stress (Longitudinal Joints) the Eq.(5) shows the *MAWP*, R_c is the $R + LOSS + FCA$, *FCA* is the specified future corrosion allowance, *LOSS* is the metal loss in the shell prior to the assessment equal to the nominal, *R* is the inside radius, *S* is the allowable tensile stress of the shell material evaluated at the design temperature per the applicable construction code, *E* is the weld joint efficiency from the original construction code, if unknown use 0.7.

$$MAWP^{C} = \frac{SEt_c}{R_c + 0.6t_c} \tag{5}$$

where t_c is the $t_{am} - LOSS - FCA$,

$$t_c = t_{am} - FCA - LOSS = 0.860 - 0.100 - (1.25 - 0.8) = 0.310 in$$

The Equation (6) shows the membrane stress. Thus,

$$\sigma_m^C = \frac{P}{E}\left(\frac{R_c}{t_c} + 0.6\right) \quad (6)$$

The Eq. (7) was true, but the level 1 assessment criteria are not satisfied. If the vessel is derated, the permissible *MAWP* based on level 1is:

$$MAWP^C = \frac{SEt_c}{R_C + 0{,}6t_c} = \frac{19998.02 \times 0.85 \times 0.310}{40.55 + 0.6 \times 0.310} = 129.36\, psi \quad (7)$$

As level 1 was not satisfied, should use level 2, so for determine if the component is acceptable for continued operation the Eq. (8) must be true.

$$t_{am}^S - FCA \geq RSFa \times t_{\min}^C \Rightarrow 0.860 - 0.100 \geq 0.90 \times 0.94 \Rightarrow 0.760 in \geq 0.846 in \quad (8)$$

The Eq. (8) is false, then the level 2 criteria are not satisfied. If the vessel is derated, the permissible *MAWP* is:

$$MAWP^C = \frac{SEt_C}{R_C + 0{,}6t_C} = \frac{19998.02 \times 0.85 \times \frac{(0.860 - 0.100 - (1.25 - 0.8))}{0.9}}{40.55 + 0.6 \times \frac{0.310}{0.9}} = 143.66\, psi \quad (9)$$

where t_c is the 0.310 in.

From the standard API 579 fitness for service were obtained two *MAWP* maximum working pressures (148.87 psi and 165.31 psi) so that the equipment continues to operate, taking into account the *FCA* (Future Corrosion Allowance). Next, realize the numerical analysis modeling of pressure vessel.

3. NUMERICAL ANALYSIS

Using the NX numerical software, is developed a model of the pressure vessel with the metal loss region obtained by ultrasound test. The pressure vessel was modeled by 50000 elements and work pressure of 400 psi and temperature of 350F.

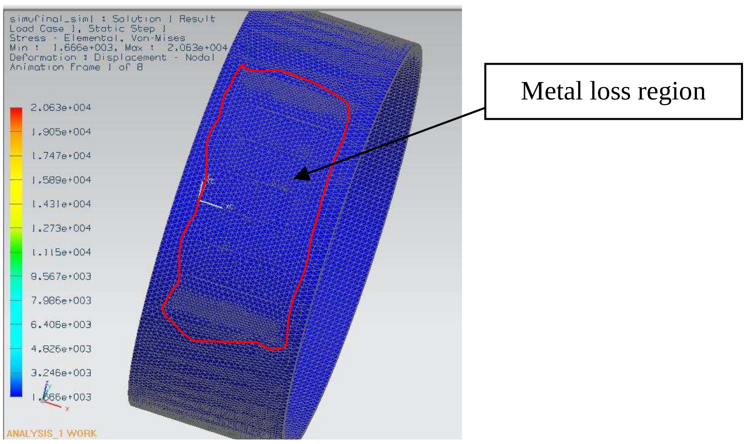
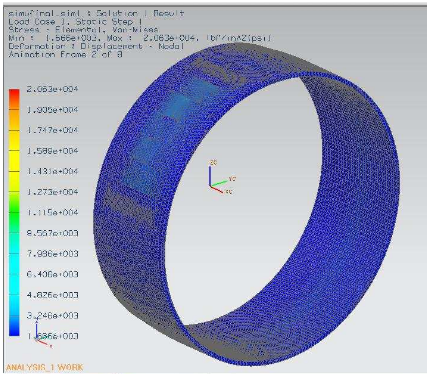


Figure 4. Modeling of the pressure vessel with metal loss region.

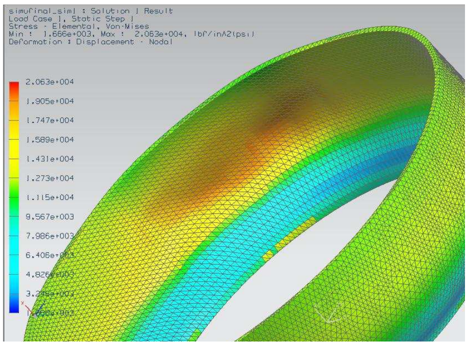
In the Figure 5 shows the behavior of stresses in pressure vessel under internal pressure and temperature of 350F.



(a)

Figure 5. Stress analysis of the pressure vessel for a working pressure 400 psi.

Numerical results show that the stress reached a value close to 20 Kpsi, which exceeded the allowable stress of 19.9 Kpsi. In this case, the working pressure should be decreased. See the Fig. 6, the highest stresses (red) are located in the damaged region, both on the external side as inside of the pressure vessel.



(a)

Figure 6. Stress in the external side and inside of the pressure vessel.

From the fitness for service API 579 analysis made, the *MAWP* was of 129.36 psi. Then, the numerical analysis was performed for this new operating pressure. The Figure 7 shows the stresses for the external side and inside of the vessel.

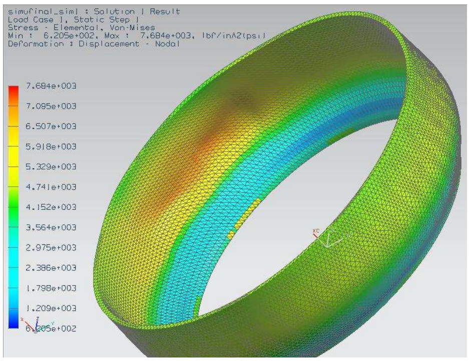


Figure 7. Stress analysis of the Internal region of metal loss.

The maximum stress (red) observed was 7.69 Kpsi which is less than the allowable stress. For the *MAWP* of 143.66 psi, the Fig. 8 shows the stress analysis.

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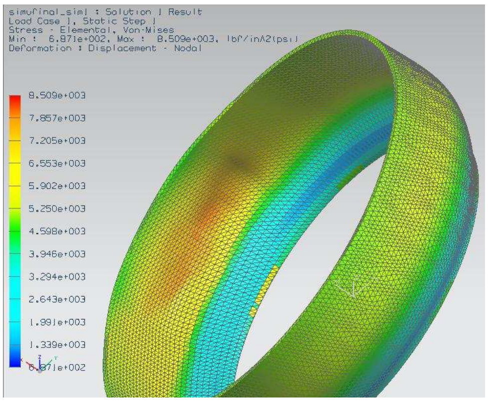


Figure 8. Stress analysis of the Internal region of metal loss;

The maximum stress (red) observed was 8.50 Kpsi which is less than the allowable stress. In the first analysis considers the profile with the *FCA* applied to each region's value eroded. For the case of the pressure vessel with future corrosion allowed (*FCA*) of 0.1 in, the vessel will support a maximum pressure of 335 psi, that for the thickness given by the ratio of the nominal thickness minus the *FCA*, see the Fig. 9.

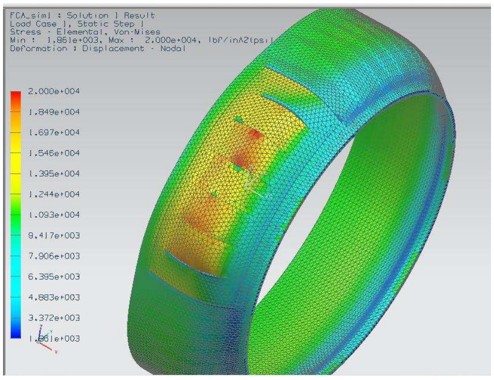
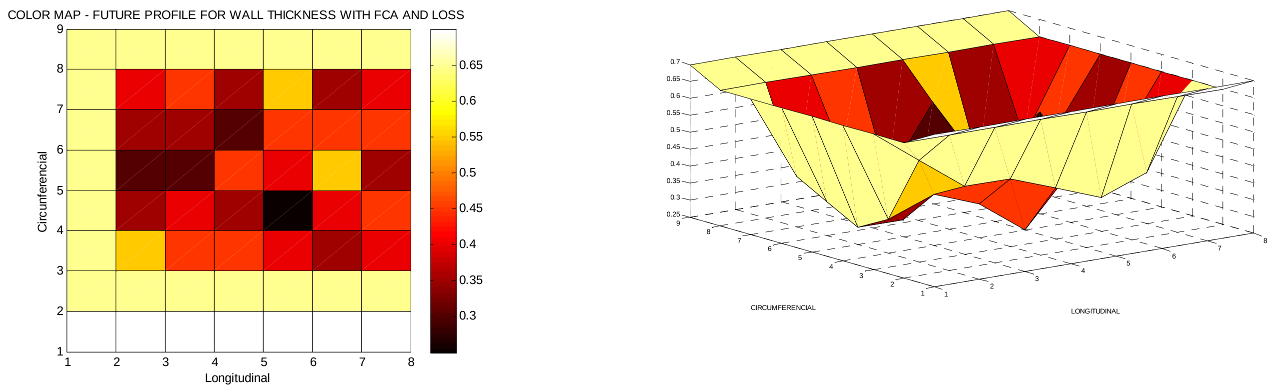


Figure 9. Stress analysis for the pressure vessel with only FCA.

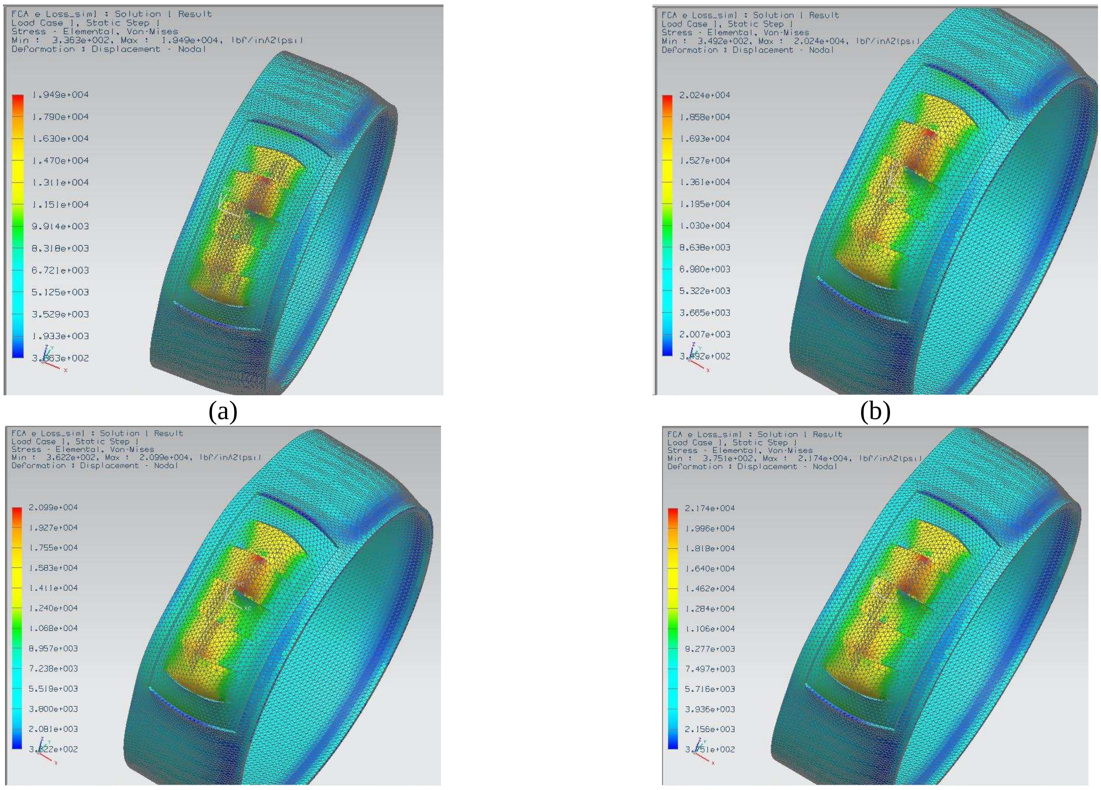
The figure shows that the allowed stress was reached at a pressure of 335 psi. Next analyze the pressure vessel with *FCA* and *LOSS* according to the level 1 and 2 of API 579. Next in the Fig. 10, shows the wall thickness profile considering the *FCA* and *LOSS* when the pressure vessel continues to operate with *MAWP* calculated by API 579 (levels 1 and 2).



(a) (b)

Figure 10. Future profile for wall thickness with *FCA* and *LOSS*.

The profile above shows the wall thickness data on minimum values of 0.25 in when applied the *FCA* and *LOSS*. In the Fig. 11 presents the numerical analysis of stress for the pressure vessel with *FCA* (0.1in*)* and *LOSS* (0.45 in). See that the damaged region had higher stresses.



(a) (b) (c) (d)

Figure 11. Numerical analysis for *MAWP* of 130psi (a), 135 psi (b), 140 psi (c) and 145 psi (d).

The numerical analysis is performed to compare the values of stresses obtained with the *MAWP* by API 579 and set the new safer values of *MAWP* by numerical solution. For this, pressure values were applied until to get the allowable stress. For the *MAWP* of 130 psi, 135 psi, 140 psi and 145 psi, the stress were close to the allowable stress (19.9 kpsi) indicating that the vessel would collapse to these *MAWP*.

The standard API 579 would indicate that the *MAWP* of 143.66 psi and 129.36 psi for the component to continue operating even considering the profile of future corrosion, the numerical solution for these values indicates that the vessel does not.

4. CONCLUSION

The numerical analysis was developed and was verified that for pressure of 400 psi, the tension at the corroded region was near the allowable stress of the material, putting the pressure vessel in a state of repair. For Maximum Allowable Working Pressures (*MAWP*), 129.36 psi and 143.66 psi, by API 579 that takes into account the future loss of thickness due to corrosion, the maximum stresses were below the allowable stress of the material.

The detailed analysis can be performed to calculate the *MAWP* for the efficiently and safely operation.

One way to monitor the system would perform the numerical analysis of quick, depending only on the thickness values obtained by ultrasonic testing.

The numerical results showed that the API 579 not showed conservatism, for a pressure vessel with a corroded area, the API 579 recommended the Maximum Allowable Working Pressure *MAWP* of 129.36 psi, for wall thickness profile with *FCA* is 0.1 in and *LOSS* is 0.45 in.

The numerical analysis showed that for this amount of pressure and with *FCA* and *LOSS*, the results showed that the collapse was inevitable. The stress at the damaged area exceeds the allowable stress of the material.

The study aims to develop the device of an automatic scanning system for a corroded region using ultrasound testing and develop an interface that allows the assembly of the FEM model for compares data from both API 579 standards on the numerical results.

Thus, the equipment should provide maximum efficiency and performance with complete safety.

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