Structural integrity assessment of storage tanks based on damaged surface reconstruction and finite element modelling

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Abstract. This research paper aims to discuss an analysis methodology developed for structural integrity assessment of storage tanks. Such methodology is based on the assessment of the damaged structure, considering the pre-deformed geometry, via stresses analysis. Then, a finite element model is generated, based on the deformed surface of the structural system, through laser scanning technology. This way, it is possible to detect the real geometry that explicitly includes the damages present on the studied storage tank. This way in this work, a real case study is investigated having in mind an Atmospheric Storage Tank (AST) located in an industrial floor related to the oil and gas industry. The equipment object of this analysis presents a cylindrical geometry with approximately 45 m diameter and a 14.63 m height and is utilized for diesel oil storage. The storage tank presents deformations on its shell (cylindrical surface of the structure), and in order to evaluate its Fitness-For-Service (FFS), i.e. evaluate whether the equipment is suitable to continue in operation, with existing damages, a laser scanning was performed on the storage tank shell. In sequence, the stresses analysis methodology provided by API (American Petroleum Institute) design codes was adopted to the assessment of the structural response. The results obtained along this research work show that the developed analysis methodology used for the evaluation of the damaged storage tank is very effective and also can reduce maintenance costs as well as losses due to the time that the structure needs to be out-of-operation.

Keywords: Storage tanks; Finite element modelling; Integrity assessment.

1 Introduction

AST are static equipment for use in the storage of petroleum, its products, and other liquid products. AST has an aboveground vertical cylindrical shape, it may have a closed or open top, are built from welded plates in various sizes and capacities for internal pressures approximating atmospheric pressure (internal pressures not exceeding the weight of the roof plates) [1].

Along its life cycle, it is common that the equipment to be susceptible to damage mechanisms and, aiming the best utilization of the asset, inspections routines and integrity assessment are required. Some international codes and standards provide guidance for those activities, e.g. API 653 [2] for Tank inspection, repair, alteration and reconstruction and the API 579 [3], which has procedures for integrity assessment of various types of damages and flaws.

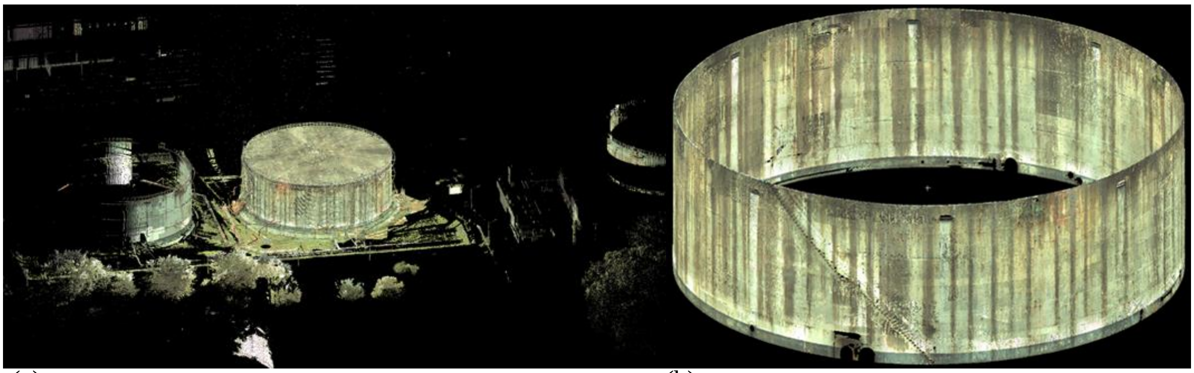
Inspection identifies damage mechanisms on equipment, e.g. corrosion and metal loss, shell distortions, shape deviation, foundation settlements, crack-like and non-crack-like flaws, etc. The most variable techniques are employed, each one with a determined effectiveness level, based on the damage/flaw type. The laser scan technique has been shown to be a practical and reliable method for identification of some kinds of flaws, like metal loss and shape deviation. It is possible to check the utilization of this technique on Arumugam's et Al. [4] work, which used a 3D laser scanner for mapping deformations in transport pipelines.

The laser scan technique was also treated in Nelson's et Al. [5] paper that performed FFS assessment on a pressure vessel corroded external surface through a laser profilometry obtained from a 3D scan. Allard and Fraser [6] mapped the external surface from a spherical pressure vessel, which has metal loss damages from corrosion, and compared the data to a theoretical reference surface, in order to quantify the depths from corrosion. The mapping with laser scanning demonstrated an advantage compared with the traditional methods because the contact between the instrument and the surface is not required, which turns out to be difficult when are damages present on the surface of the equipment. In another work, Allard and Mony [7] demonstrated the application of the laser scan for pipelines damage assessment, like corrosion and mechanical damages, using the ASME B31.G criteria [8]. The 3D laser scanning proved to be a trend and a logical evolution, compared with the usual non-destructive techniques (NDT), mainly by its high productivity. Samman et Al. [9] evaluated bulges in coke drums through deformation analyses methodologies. For that purpose, 3D laser scan measurements were performed and plastic deformations calculated from analytical formulas. Lopes [10] used laser scan techniques for mapping deformations on AST's shells for further integrity assessments based on the finite element method and provisions in API 579 [3]

This work aims to evaluate the laser scan methodology to integrity assessment of an AST through the API 579 [3] procedures, based on the finite element method. The equipment is 43.428 m in diameter, 14.63 m in height and it is used for diesel oil storage. Its shell and its fixed roof are built from ASTM A-283 Gr. C [11] plates. Shell deformations are measured by laser scan technique. The inspection results is a group of points in the space with (X,Y,Z) coordinates, also known as Point Cloud (PC), which is processed to build a surface for a Finite Element Model (FEM) meshing, representing explicitly the damages on the tank's shell. The FEM is used for the integrity assessment procedures from API 579 [3], through nonlinear stresses and buckling analyses. The results demonstrate that laser scan inspection combined with integrity assessment can reduce maintenance costs as well as ensure the safe operation.

2 Laser scan inspection

Deformations on the AST's shell were measured with 3D laser scan techniques. For that, the C10 model of the Leica Geosystems Terrestrial Laser Scanner was used. This step focuses on mapping the AST's shell in order to develop a FEM more similar to the actual deformed structure. The result of the 3D laser scan was a raw PC, with several other elements which were scanned as a secondary way, like piping systems, valves, structures, scaffolds, others AST's and equipment, trees, etc. After the laser scanning, was necessary to process the PC in order to remove these others unwanted elements for the posterior FEM analyses. The PC processing was performed at the Cyclone 9.0 software and Fig.1 shows the results.



(a) (b)

Figure 1. Raw PC (a) and processed (b).

The PC of the AST's shell it is just a group of points in a table with spatial coordinates (X,Y,Z). Although it treats point-by-point the AST's shell deformations very precisely, the FEM mesh preparation from a PC is not a trivial task. For that, was necessary to postprocess the PC on the Cyclone Reshaper software to convert it in a STL format surface for posterior utilization on the ANSYS software. In ANSYS, the "Skin Surface" resource was used to transform the STL format surface in an appropriate surface to be meshed for the FEM (Figure 2 shows the details of the surface and circled in red the most relevant deformations on the shell).

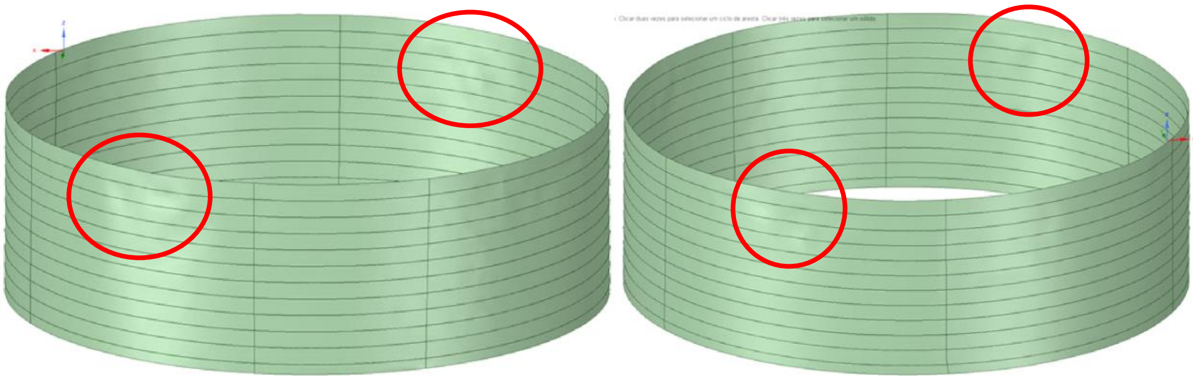


Figure 2. Post-processed surface for finite element meshing.

3 Finite element modelling

From the reconstructed surface, the FEM was prepared on the ANSYS Mechanical v18.0 software. The first step was to assign a thickness value to each one of the six shell courses, which can be observed in Tab. 1. The loads acting are the deadweight of the AST's shell and its fixed roof (simply supported on the shell), the hydrostatic pressure of the stored liquid and wind loads (only considered for buckling analysis). The deadweight from the fixed roof plates was applied as a force of 60 kN distributed on the top of the 6th shell course. The deadweight of the AST's shell it's calculated automatically from the specific mass of the steel (7850 kg/m³) and by the standard gravitational acceleration (9.81 m/s²). The hydrostatic pressure was calculated from the water density (1000 kg/m³), the stored liquid level inside the tank (at the top of the 6th shell) and the standard gravitational acceleration.

Table 1. FEM Shell thickness

Shell	Thickness (mm)
1°	20.51
2°	15.88
3°	15.88
4°	9.53
5°	7.94
6°	7.28

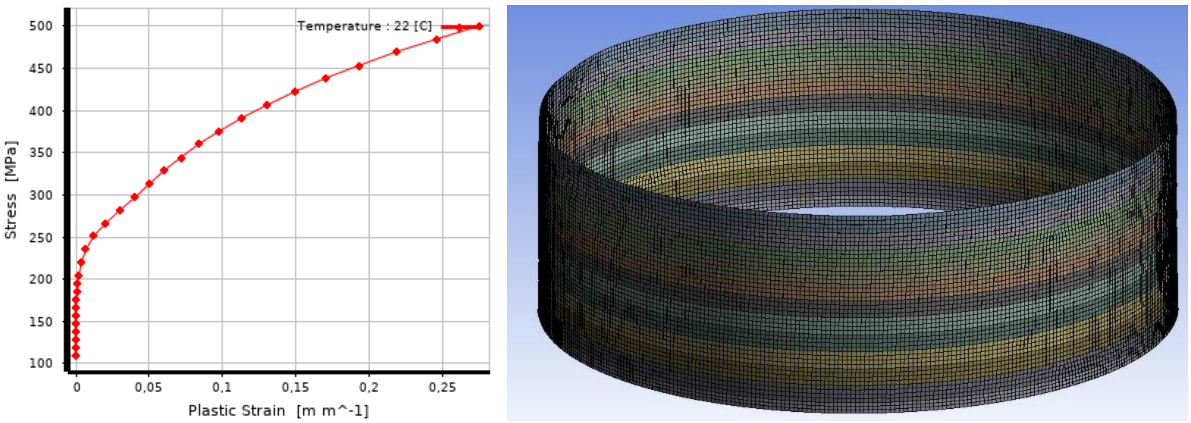


Figure 3 – Stress-strain curve model (a) and finite element mesh (b).

Despite the fact that diesel oil is stored in the AST, the water being considered as the fluid for the hydrostatic pressure calculations is a conservative hypothesis, because the density of water is higher than that of diesel and because the tank can be hydrostatically tested (with water). The wind loading was inserted as a pressure on the AST's shell in four different directions on the cartesian plain (X,Y), with the ABNT NBR 6123 [12] calculation procedures which parameters are available on Tab. 2.

Table 2. Wind load calculation parameters from ABNT NBR 6123 [12]

Parameter	Value
V_0	38 m/s
S_1	1.00
S_2	1.04
S_3	1.00
V_k	39.52 m/s
q	957.4 N/m²

Soil and foundation parameters were not available so the model was constrained, in a simple way, as null displacements at the first shell course bottom part, representing a simple supported shell above a concrete ring wall. Another hypothesis is that the soil is stabilized without settlements and/or other foundation problems.

4 Elastic-plastic nonlinear analyses

The equipment integrity was evaluated from the API 579 [3] criteria, for three different failure modes: Protection against plastic collapse, protection against local failure and protection against collapse from buckling. For the plastic collapse and local failure criteria, the load case combinations are according with Table 2D.4 from API 579 [3]. So, in this case, the load combinations are:

$$\text{Plastic collapse - } \beta(P + P_s + D) = 2.25(P_s + D). \tag{1}$$

$$\text{Local failure - } 1.7(P + P_s + D)RSF_a = 1.53(P_s + D). \tag{2}$$

Where:

P: Internal pressure; P_s: Hydrostatic pressure; D: Deadweight; RSF_a: Allowable Remaining Strength Factor, 0.9 recommended value from API 579 [3]; and β: Parameter from Table 2D.5 do API 579 [3] and for API 650 AST, β=2.25

The protection against plastic collapse and local failure were performed trough the elastic-plastic analysis criterion from API 579 [3]. For the plastic collapse, it is necessary to achieve the convergence of the nonlinear analysis to guarantee the equipment protection. For the local failure criterion, the Eq. (3) must be satisfied.

$$\frac{\varepsilon_{peq} + \varepsilon_{cf}}{\varepsilon_L} \leq 1.0. \tag{3}$$

Where:

ε_{peq}: Equivalent plastic strain, obtained from the FEM analyses.

ε_{cf}: Cold forming strain of the shell's plate (from ASME PCC-2 [13]).

ε_L: Plastic strain limit, given from Eq. (4).

$$\varepsilon_L = \varepsilon_{Lu} exp\left[-\left(\frac{\alpha_{sl}}{1 + m_2}\right)\left(\left\{\frac{\sigma_1 + \sigma_2 + \sigma_3}{2\sigma_{eqv}}\right\} - \frac{1}{3}\right)\right] \tag{4}$$

For more details of the procedure and parameters, the API 579 [3] must be consulted.

In the first analysis, the convergence was not achieved for the plastic collapse criterion indicating that the tank was not fit for service. In order to converge the analysis, the liquid level was reduced until the half-height of the 6th shell course (approximately 13.4 m) and a second analysis was performed, which achieved the convergence, i.e., the tank is suitable for operation under such conditions. Figure 4 shows the results in terms of membrane stresses (Fig 4-a) and the equivalent plastic strains (Fig. 4-b).

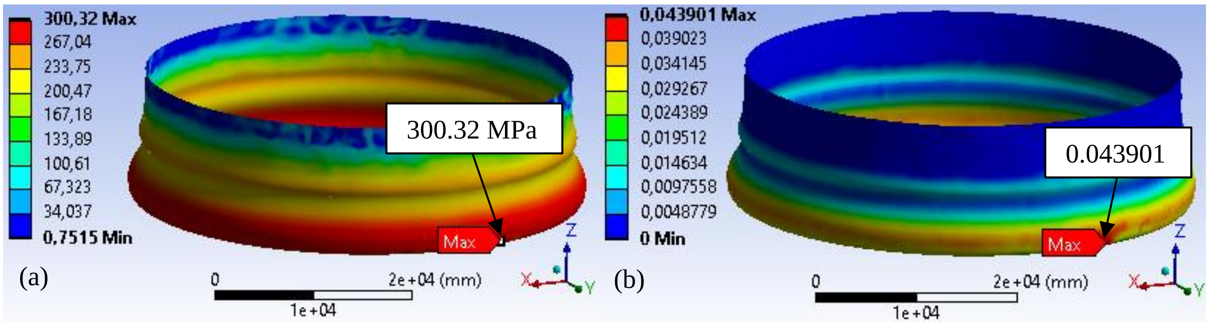


Figure 4. Membrane stresses in MPa (a) and the equivalent plastic strains (b).

For the local failure criterion the nonlinear analysis achieved the convergence and Fig. 5 demonstrates the results in terms of equivalent plastic strains (Fig. 5-a); cold forming strains (Fig. 5-b); local failure criteria (Fig. 5-c); and membrane stresses (Fig. 5-d). All values on Fig. 5-c are below 1, indicating that Eq. (3) it is satisfied.

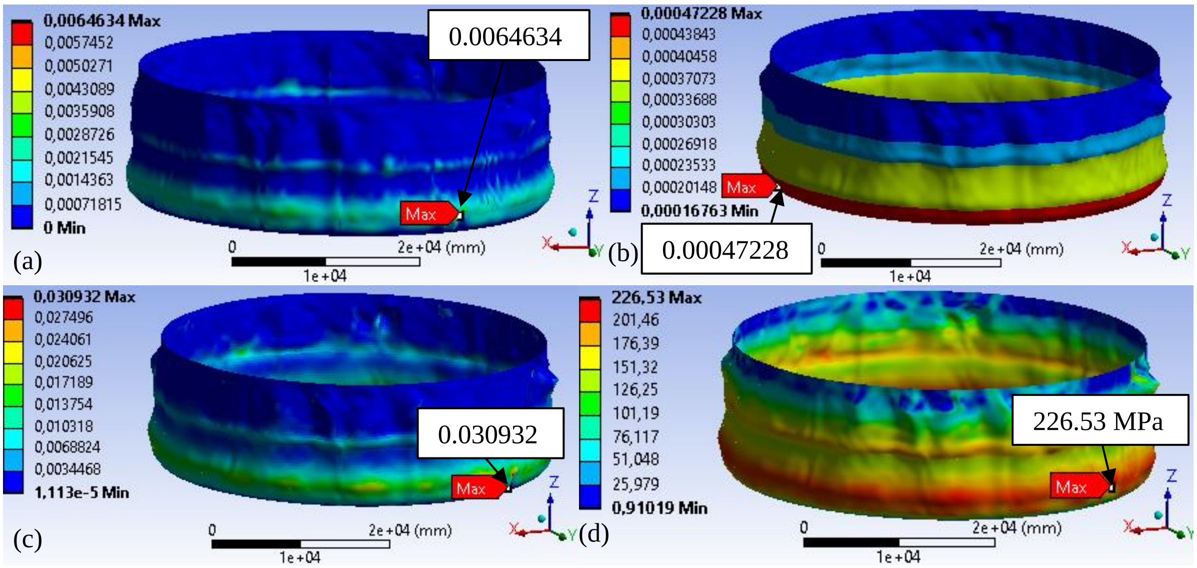


Figure 5. Equivalent plastic (a) and cold forming (b) strains; local criterion (c) and membrane stresses (MPa) (d).

5 Wind load buckling analysis

The buckling criterion was evaluated for the empty condition of the tank (or with a very low level of product stored), subjected to wind loads. In this situation, the stresses field presents a compressive behavior, which can contribute to instability of the structure and posterior buckling. For the protection against collapse from buckling, a Type 3 analysis of API 579 [3] was performed. This analysis is indicated in cases where the elastic-plastic method was performed to evaluate plastic collapse and the imperfections are explicitly considered in the analysis model geometry. In that case, the load combinations are also in accordance with Table 2D.4 from API 579 [3], and the 4th case is the only one applied, as it possible to see in Eq. (5), where W is the wind load.

$$Load\ Case\ 4 \rightarrow\ 1.98D + 1.6W. \quad (5)$$

The ANSYS software presents the answer in terms of a factor regarding the critical buckling loads, related to the buckling modes (eigenvalues and eigenvector buckling analysis). Thus, in that way, analyses were performed in order to find a wind load W that, together with the deadweight which is constant, results in a load factor of 1 (or very close to 1) and satisfies the Eq. (6) criterion.

$$\frac{W}{1.6} \geq 957.4\ N/m^2. \quad (6)$$

The first analysis was performed with the wind on the negative X-axis direction. In this case, a critical wind pressure load of 837.44 N/m² was found, which does not satisfy the Eq. (6) criterion. As a way to simulate repair conditions in the shell of the AST to reinforce it, structural steel elements of 4”x4”x1/2” dimensions were inserted in the model (to be welded in the actual tank) in order to rise the stiffness of the structure. The steel elements, welded along the entire circumferential perimeter and in the half-height of the 4^{th}, 5^{th} and 6^{th} shell courses can be seen in the Fig. 6.

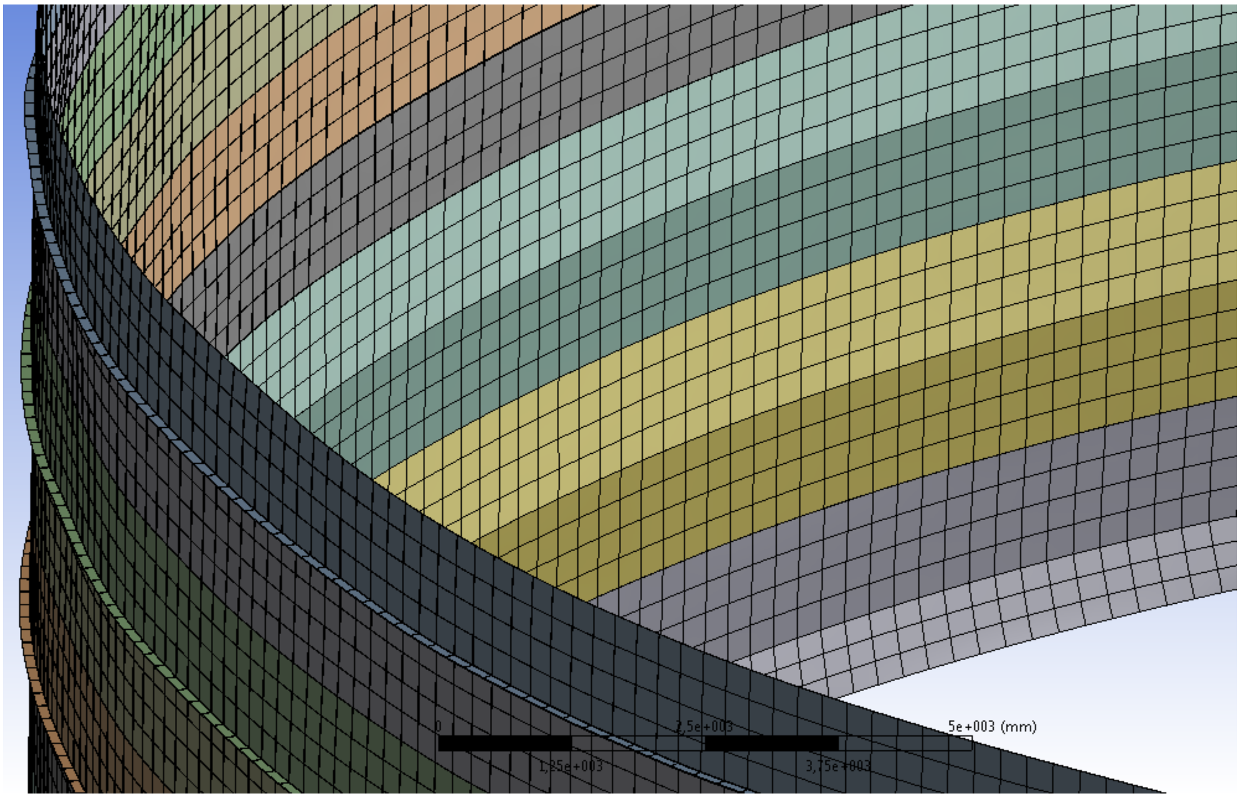


Figure 6. Reinforced shell meshes details.

For the new model, after the analyses, the results of the eigenvalues (load factors) are available in Tab. 3. It is possible to observe that all values on “Criterion” column are above the 957.4 N/m², i.e., the structure of the shell of the AST is protected against collapse from buckling, based on API 579 [3] criterion.

Table 3. Load factors from eigenvalue buckling analyses

Wind Direction	Critical Wind Load W (N/m²)	Load Factor	Criterion (N/m²)	OBS
X positive	1805.6	1.0048	1128.50	Criteria satisfied
X negative	2393.8	1.0001	1496.13	Criteria satisfied
Y positive	2304.7	1.0001	1440.44	Criteria satisfied
Y negative	2663.8	1.0001	1664.88	Criteria satisfied

6 Conclusions

The main conclusions of this study focused on the integrity assessment of AST, based on finite element mesh reconstruction through 3D laser scan techniques for surface damages mapping. The methodology here presented shows that:

1. The use of the laser scanner allowed the explicitly representation of the deformations in shell courses of the AST, considering the actual geometric imperfections in the structure. In this way, it was possible to build a FEM suitable for the assessment of the flaws present in the actual equipment.

2. The nonlinear analysis for the plastic collapse criterion indicated a 300.32 MPa maximum membrane stress level and a 0.043901 maximum equivalent plastic strain.

3. For the local criterion, the maximum membrane stress level was 226.53 MPa, while the maximum

equivalent plastic and cold forming strains were, respectively, 0.0064634. The found values led to a 0.030932 criterion from API 579 [3], which indicates that Eq. (3) has been met.

4. The assessment of the tank indicates that the maximum level of stored product must not exceed the half height of the 6th shell course, i.e., 13.4 m.

5. For the buckling criterion the maximum wind load pressure which the AST can be subjected to was 1805.6 N/m² in the X positive direction, which attends the API 579 [3] criterion, considering the ABNT NBR 6123 [12] parameters.

5. Wind induced buckling can be prevented by steel reinforcement structural elements, which must be welded along all the circumferential perimeter on the half-height of the 4th, 5th, and 6th shell courses.

7. The calculations demonstrate that the AST is suitable for operation since the premises presented in this study and the remarks of the 4th and 6th conclusions are satisfied.

8. The laser scan technique demonstrates to be handy for the deformation measurements and a very quick method to inspect geometric imperfections on the shell. Besides that, conventional local measurements require scaffolding and human exposure to work at height, situations which the laser scanning avoids.

9. The methodology presented in this paper shows a maintenance cost reduction scenario, considering that the shell course plates do not need to be replaced for new ones, with no deformation.

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