Buckling analysis of storage tanks based on the use of geometric imperfections measured by laser scan dimensional inspection techniques

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Abstract. Storage tanks are thin-walled equipment often subjected to wind loadings, which may lead the equipment to structural instability. The critical buckling load of storage tanks are too sensitive to structural imperfections, that can be present at its structure taken into account damage mechanisms which tend to reduce the structural integrity of this type of equipment along its life cycle. Inspection techniques are employed to characterize damage mechanisms, which in turn are assessed to evaluate whether or whether not the equipment may have a safe operation. The laser scan technique has been shown to be accurate in dimensional inspection of storage tanks. This paper focuses on the structural integrity assessment of an actual damaged surface of a real storage tank. The tank is 43.428 m in diameter and 14.63 m in height and is used for diesel storage. Deformations are present at the structure of the tank, which are measured with an industrial laser scan. The point cloud resulting from the dimensional laser scan inspection is used to build a finite element model taken into account all geometric imperfection. Geometric and Material with Imperfection Nonlinear Analyses (GMNIA) are performed considering different load combinations and different wind pressure coefficients to assess plastic collapse, excessive local plastic strain failure and buckling. Simulations considering structural steel shapes at the shell of the tank are performed to evaluate failure from wind induced buckling, once the structural integrity of the equipment is reduced by deformations present at the structure of the tank. The results show that the equipment

Keywords: Storage Tanks, Wind Induced Buckling, Laser Scan Inspection, Nonlinear Analysis, Integrity Assessment

1 Introduction

Storage tanks are normally used for petroleum and related products storage. This type of equipment is vertical shaped and aboveground, closed or opened-top, and built on steel plates in different capacities and sizes, for internal pressures approximating atmospheric pressure [1,2]. Along its life, tanks are exposed to several damage mechanisms. Inspections and integrity assessments are necessary to evaluate whether the tank is suitable for operation or, otherwise, whether maintenance is required. Some international codes and standards provide guidance for these activities, e.g., API 653 [3] and API 579 [4], which have procedures for integrity evaluation.

Inspection routines aims to identify metal loss and corrosion, shape and shell distortions, foundation settlements, crack and non-crack-like flaws and several other damage mechanisms. Different techniques are employed, with a determined effectiveness level, depending on the damage or flaw. A practical technique for identification of flaws like metal loss and shape deviation are the laser scan inspection technique, which has been shown to be reliable method for dimensional inspection.

Laser scanner for 3D mapping of deformations in pipelines was used on Arumugam's et Al. [5] work. Nelson's et Al. [6] paper covered the laser scan technique allied to Fitness-For-Service procedures to assess the integrity of a corroded surface of a pressure vessel. Corrosion depths at the external surface of pressure vessel were also mapped with laser scan by Allard and Fraser [7]. Laser scan application for damage assessment on pipelines, like corrosion and mechanical damages, was demonstrated by Allard and Mony [8] using the ASME B31.G criteria [9]. Evaluation of coke drums containing bulges was presented by Samman et Al. [10] through strain analyses methodologies, using laser scan measurements.

This work evaluates the laser scan methodology for storage tanks integrity assessment using API 579 criteria, based on nonlinear finite element simulations. A real storage tank was mapped by a laser scanner for shell distortions measurements. The equipment diameter and height are, respectively, 43.428 m and 14.63 m. The tank stores diesel oil and its shell and fixed roof are built from ASTM A-283 grade C [11] plates. The resulting point cloud from the laser scan inspection was used to prepare a finite element mesh, explicitly representing the shell distortions. Nonlinear stresses and buckling analyses were performed and results show that laser scan inspection, allied with integrity assessment, can ensure a safe operation as well as reduce maintenance costs.

2 Dimensional inspection

The shell distortions of the tank were measured by the C10 model of the Leica Geosystems Terrestrial Laser Scanner, shown in Fig. 1. The objective of this step was the 3D mapping of the shell to develop a finite element mesh more similar to the actual structure, accounting explicitly the geometric imperfections. The result of the dimensional inspection was a raw point cloud containing several unwanted scanned objects like structures, valves and piping systems, scaffolds and others. A cleaning process on the raw point cloud was required to remove the unwanted scanned objects for the posterior finite element analyses, for that, the Cyclone 9.0 software was used (see Fig. 2).

Figure 1. C10 model terrestrial laser scanner from Leica Geosystems

Figure 2. Cleaned point cloud

The cleaned point cloud had to be post processed in order to develop a finite element mesh. The first step on this post-processing was to sample the cleaned point cloud to reduce the number of points. The Meshlab 2020.12 software was used for that purpose, using the Poisson-Disk Sampling method proposed by Corsini et al. [12]. Then, the sample point cloud was used to calculate the radial distortions, considering the design diameter of the tank and each coordinate of each point from the sample point cloud. For that, a simple script on MATLAB R2015b software was used. The result of that post-processing was a table containing the radial distortions of the shell for each coordinate (X,Y,Z), used posteriorly for the finite element meshing.

3 Finite element modelling

The ANSYS Mechanical v18.0 [13] software was used for the finite element analyses. Table 1 presents the shell thicknesses for the six courses of the tank considered for the model. The analyses considered the following loads: Hydrostatic pressure of the stored product; deadweight from the equipment; and wind pressure load (for buckling analysis). Hydrostatic pressure was automatically defined by the software, taking into account the density of water, the standard gravitational acceleration and maximum stored liquid level. Deadweight was considered for the shell plates and fixed roof. For the shell plates, the deadweight was automatically calculated by the software with the specific mass of the steel, the structural volume and standard gravitational acceleration. For the fixed roof, the deadweight was considered as a 60 kN force.

Table 1. Shell thicknesses per course

Shell course	Thickness (mm)
1^{st}	20.51
2^{nd}	15.88
3^{rd}	15.88
4^{th}	9.53
5^{th}	7.94
6^{th}	7.28

The equipment stores diesel oil. However, consider water for the hydrostatic pressure was a conservative hypothesis, because the density of water is higher than that of diesel and the tank can be used to store water. Loads from wind were applied at the shell in four different directions on the Cartesian plain (X,Y), with the guidelines from ABNT NBR 6123 [14] which parameters used are available in Tab. 2. The bottom of the first shell of the model was constrained and for the material nonlinearities an isotropic hardening plasticity constitutive model was utilized, considering a multilinear behavior (Fig. 3 left). A quadratic shell element (SHELL281 from ANSYS element library) with eight nodes and six degree of freedom per node was used for the meshing process, resulting in model with 66727 nodes and 21961 elements (Fig. 3 right). To obtain the deformed model mesh, a previous linear elastic analysis was performed with the radial distortions, from the sample point cloud, as load displacements. The deformed mesh was used to assess failure modes criteria from API 579 [4].

Table 2. Calculation parameters for wind loads

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 Pa

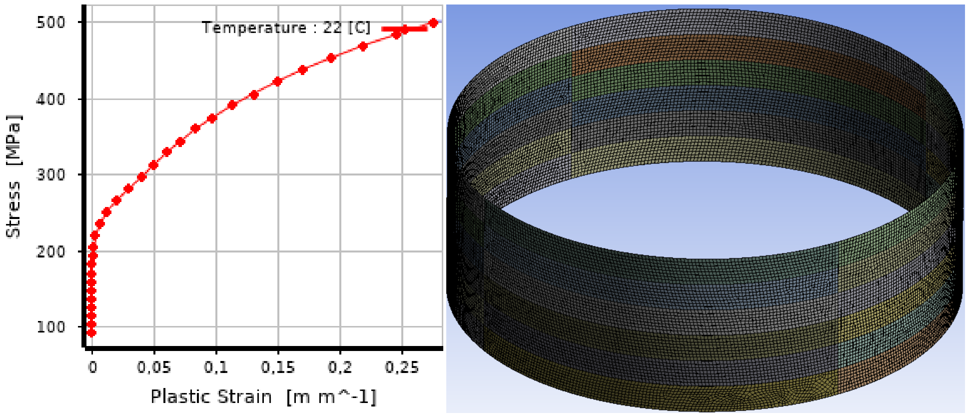

Figure 3. Cleaned point cloud

4 Stress and strain analyses

Three different failure modes criteria were evaluated according to API 579, i.e., plastic collapse, local failure and buckling. Load case combinations from Table 2D.4 [4] were considered for the plastic collapse and local failure criteria, defined by Eq. 1 to 4, where P: Internal pressure; P_s: Hydrostatic pressure; and D: Deadweight.

$$\beta(P + P_s + D) = 2.25(P_s + D) \tag{1}$$

$$1.7(P + P_s + D)\mathrm{RFS_a} = 1.53(P_s + D) \tag{2}$$

$$RSFa = 0.9\ [4] \tag{3}$$

$$\beta = 2.25\ [4] \tag{4}$$

The protection against plastic collapse and local failure were assessed through elastic-plastic analyses. The criterion to evaluate plastic collapse was the nonlinear analysis convergence, considering load combination from Eq. 1, to guarantee the equipment protection. Strain analysis defined by Eq. 5 had to be satisfied (considering load combination from Eq. 2) for the local failure criterion, where ε_{peq}: Equivalent plastic strains; ε_{cf}: Cold forming strain of the steel plates (from ASME PCC-2 [15]); and ε_L: Plastic strain limit, given from Eq. 6.

$$\frac{\varepsilon_{peq}+\varepsilon_{cf}}{\varepsilon_L} \leq 1.0 \tag{5}$$

$$\varepsilon_L = \varepsilon_{Lu} exp\left[-\left(\frac{\alpha_{sl}}{1+m_2}\right)\left(\left\{\frac{\sigma_1+\sigma_2+\sigma_3}{2\sigma_{eqv}}\right\}-\frac{1}{3}\right)\right] \tag{6}$$

The nonlinear analysis convergence has been achieved with liquid level reduced to the half-height of the 6th shell course (approximately 13.4 m), i.e., results indicated that the tank was suitable for operation under such conditions without the occurrence of plastic collapse. Figure 4 provides membrane stresses and equivalent plastic strains from the analysis. The convergence for the local failure nonlinear analysis was also achieved and the results are available in Fig. 5. It is important to emphasize the results in Fig. 5 (d), which represents Eq. 5 along the shell. The protection against local failure criterion was met because all values are below 1 in Fig. 5 (d). The nonlinear analyses were performed considering the large displacement effects through the full Newton-Raphson procedure. This solution procedure updates the stiffness matrix every iteration, until convergence is achieved.

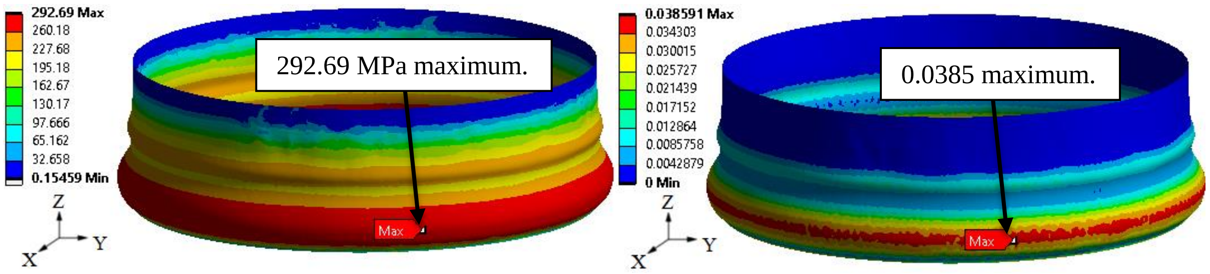

Figure 4. Membrane stresses in MPa (left) and equivalent plastic strains (right).

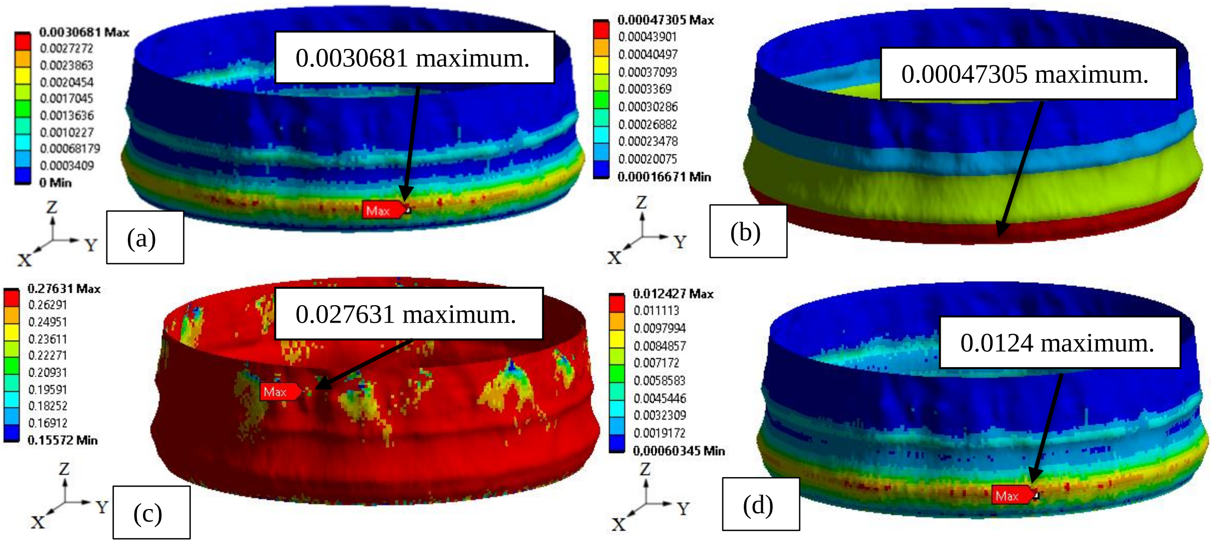

Figure 5. Equivalent plastic (a) and cold forming (b) strains; strain limit (c) and local failure criterion (Eq. 5) (d).

5 Nonlinear buckling analysis

The assessment of the buckling criterion was considered for the empty condition of the tank subjected to wind loads. In this situation the stresses field presents a compressive behavior, which can contribute to the structural instability and buckling may occur. The 4th load combination case from Table 2D.4 (Eq. 7), which was the only applicable, was used to perform a geometric and material nonlinear with imperfection analysis (GMNIA). Structural stability is indicated by the nonlinear analysis convergence considering load combination in Eq. 7, where W is the wind load.

$$1.98D + 1.6W \tag{7}$$

The actual tank shell buckling analysis results indicated structural instability for the 957.4 Pa (1531.84 Pa with 1.6 load factor) wind pressure. Structural steel shapes (see model in Fig. 6) on the actual deformed tank shell were simulated to evaluate the buckling resistance and the results indicated structural stability. Wind pressure versus displacement curves for each analysis is available in Fig. 7 and summary results in Tab. 3.

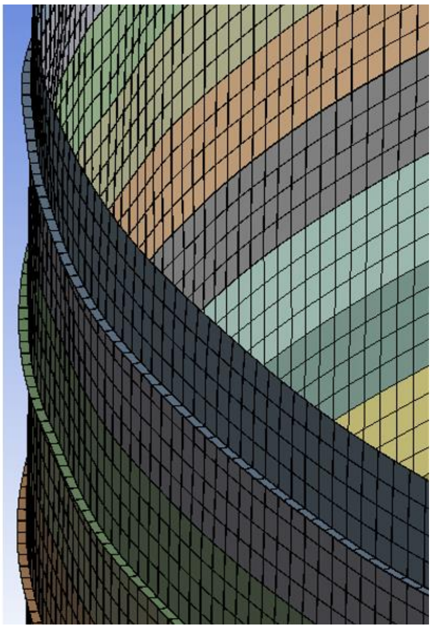

Figure 6. Finite element model details for the structural steel shapes

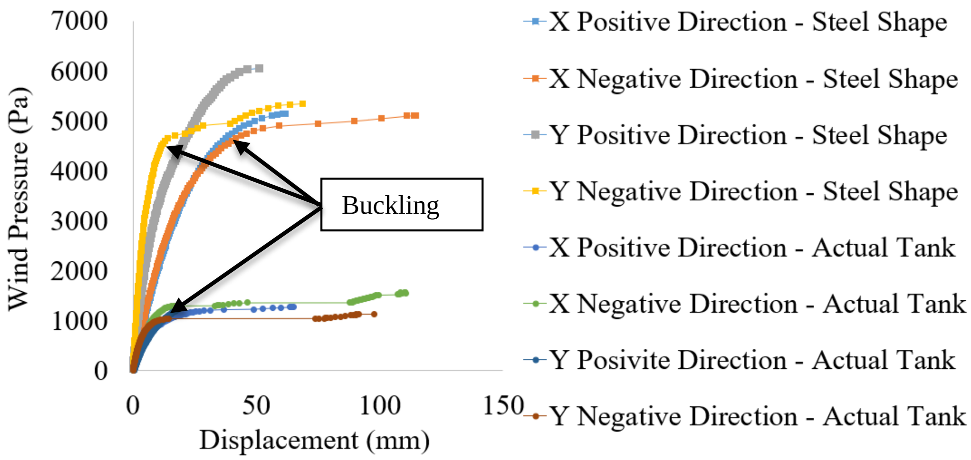

Figure 7. Wind pressure load versus displacement curves for the buckling analyses.

Table 3. Summary results from nonlinear buckling analyses.

Wind direction	Shell condition	Critical buckling pressure (Pa)	Criterion
X axis positive	Actual	1275.3	Not met.
X axis negative	Actual	1571.1	Met
Y axis positive	Actual	1253.8	Not met.
Y axis negative	Actual	1126.9	Not met.
X axis positive	Steel Shapes	5141.6	Met
X axis negative	Steel Shapes	5113.1	Met
Y axis positive	Steel Shapes	6050.0	Met
Y axis negative	Steel Shapes	5335.0	Met

6 Conclusions

The main conclusions of this paper regard the assessment of storage tanks integrity, based on nonlinear finite element analyses assisted by laser scan inspection techniques. The presented methodology shows that:

1. The laser scanner allowed representing explicitly the deformations at the shell of the tank, considering the imperfections in the actual structure. Thus, it was possible to develop a finite element model suitable for the assessment of the deformations present in the structure of equipment. Also, the laser scan demonstrates to be very handy for dimensional inspection.

2. Nonlinear analyses performed to assess plastic collapse and local failure criteria indicated that the storage tank was suitable for continued operation concerning the maximum level of stored product at the half height of the 6th shell course, i.e., 13.4 m.

3. Nonlinear buckling analyses allowed concluding that the investigated tank was not fit for service considering wind pressure load. The buckling analyses indicated structural instability, considering the actual structure of the tank shell.

4. Structural steel shapes are a good practice to prevent wind induced buckling. The structural shapes must be welded along the circumferential direction at the half-height of the 4th, 5th, and 6th shell courses to quite increase the stiffness of the tank.

5. The analysis methodology developed in this investigation shows a maintenance cost reduction scenario, taking into account that the shell plates do not need to be replaced.

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