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Nonlinear dynamic analysis of storage tanks when subjected to nondeterministic wind loadings

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Abstract. Storage tanks are associated to thin-walled equipment subjected to wind-induced loads, which can lead the system to structural instability. The storage tanks behavior is too sensitive to imperfections that can be present on the structural system, taken into account damage mechanisms which tend to reduce the integrity of this type of equipment along its service life. In fact, inspection techniques are employed to characterize the damage mechanisms. This way, the laser scan technique has been shown to be accurate in dimensional inspection of storage tanks. Therefore, this research work focuses on the nonlinear dynamic analysis of an actual damaged surface related to a storage tank. The investigated tank presents a diameter of 43.428 m and height of 14.63 m, and is used for diesel storage. The deformations present on the tank structure were measured based on the use of a laser scan. The point cloud resulting from the dimensional laser scan inspection was used to build a finite element model taken into account all geometric imperfections. After that, the nondeterministic wind loadings were used to perform the nonlinear dynamic analysis considering the actual deformed structural system of the studied tank. In this investigation, the results have indicated relevant differences, when the geometric nonlinearity effects were included in the structure dynamic response assessment, when compared to those calculated based on the traditional static analysis.

Keywords: storage tanks, laser scan inspection, nonlinear dynamic analysis, integrity assessment

1 Introduction

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

Inspection routines aims to identify corrosion and metal loss, 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 is 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.

Storage tank's design normally takes into account wind loads, in addition to other normal operation loads, such as internal and hydrostatic pressure, deadweight, etc. Wind loads are usually treated as constant over time, acting on the shell surface of the storage tank. It is known that wind behavior is not constant over time and can vary a lot, which can affect the structure if is not considered in the design of the equipment. Nondeterministic wind behavior was studied by Bastos [11] and it was demonstrated that the dynamic behavior of the wind it is important to be considered.

This work evaluates the structural behavior of a real storage tank which has deformations on its shell. 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 [12] plates. Deformations on the shell of the tank were measured by a 3D laser scanner, which resulting point cloud was used to prepare a finite element mesh, explicitly representing the shell distortions. Nondeterministic wind loads dynamic analyses were performed in order to evaluate the structural behavior of the equipment, considering a linear elastic approach and also taking into account geometric nonlinearities for the nonlinear analyses, showing relevant differences between these two different analyses.

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

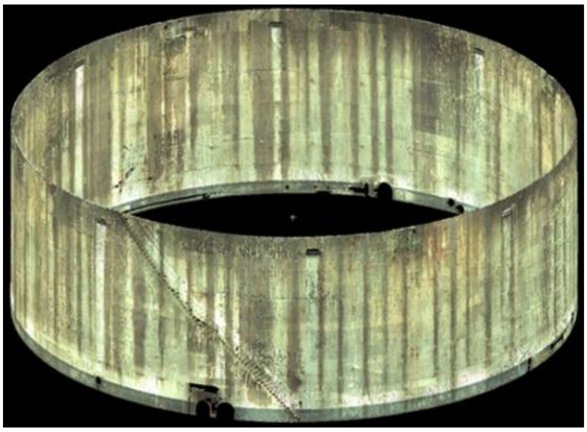

Figure 2. Cleaned point cloud

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. [13]. 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 model of the investigated tank

The ANSYS Mechanical v18.0 [14] 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 nondeterministic wind loads. Hydrostatic pressure considered 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 steel specific mass, 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 (millimetres)
1st	20.51
2nd	15.88
3rd	15.88
4th	9.53
5th	7.94
6th	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. The nondeterministic wind load was defined according to the Power Spectral Density Method, considering the Kaimal Power Spectral Density [15]. The mean portion of the wind load was calculated with the guidelines from ABNT NBR 6123 [16] which parameters used are available in Table 2. The bottom of the first shell of the model was constrained and the top of the sixth shell was modelled as a rigid region, in order to account for the fixed roof's stiffness. 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 7616 nodes and 2448 elements (Fig. 3 left). To obtain the deformed model mesh (Fig. 3 right), a previous linear elastic analysis was performed with the radial distortions, from the sample point cloud, as load displacements. The deformed mesh was used for the structural analyses.

Table 2. Calculation parameters for wind loadings

Parameter	Value
V_0	35 m/s
S_1	1.00
S_3	0.9989
b	0.85
p	0.125
Fr	0.98

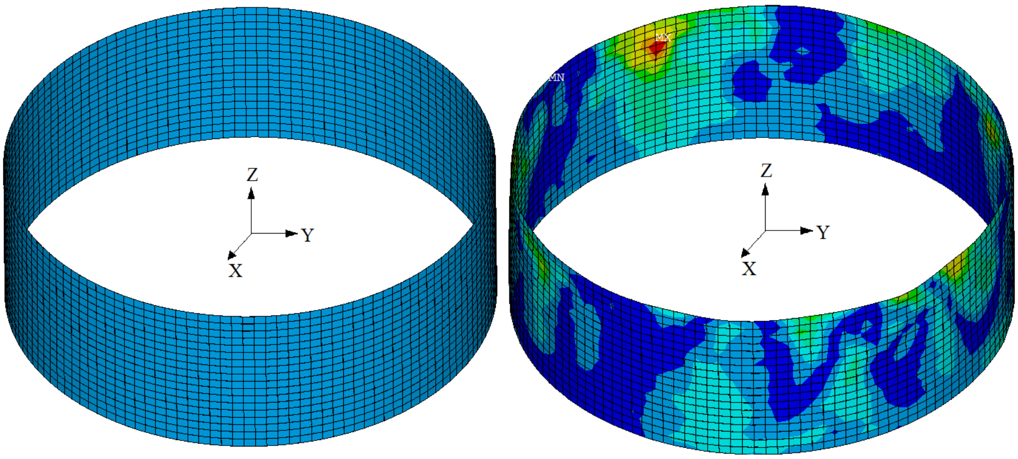

Figure 3. Finite element modelling as designed (left) and as measured (right)

4 Natural frequencies and vibration modes

The modal analysis was performed aiming to obtain the natural frequencies values and its associated mode shapes considering the prestressed effects and taking into account the operation loads, e.g., hydrostatic pressure, deadweight and fixed roof plates weight. This way, the first two modal analyses were developed based on a previous linear elastic static analysis to consider the operation loads prestress effects, regarding the design shell dimensions (without any deformations), and the actual shell dimensions (with deformations measured by the laser scanner). On the other hand, the last two modal analyses were performed based on the same operation loads considered in the first two analyses. However, in these modal analyses the prestress effects were determined considering a previous geometric nonlinear static analysis including large deflections.

This way, Table 3 presents the investigated tank natural frequencies and Fig. 4 presents the first mode shape for each condition (as previously designed and deformed). It is possible to notice that the deformed condition presents a high localized mode shape vector for the first natural frequency. This is an expected behaviour, once the imperfections present in the shell of the tank can modify the local stiffnesses of a highly deformed region of the structure, considering the thin cylindrical surface without any imperfections.

Table 3. Natural frequencies of the investigated tank

Natural Frequencies (Hz)	Linear: as designed	Linear: deformed	Nonlinear: as designed	Nonlinear: deformed
1	13.05	12.63	12.96	12.46
2	13.05	12.66	12.96	12.59
3	13.06	12.73	12.99	12.64
4	13.06	12.76	12.99	12.75

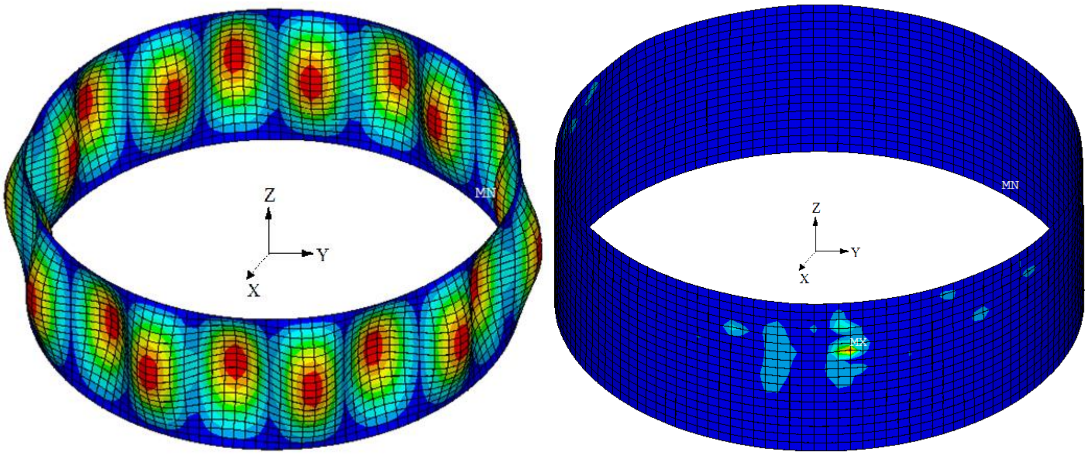

Figure 4. First modal shape for the design condition (left) and deformed (right).

5 Forced vibration analysis: nondeterministic wind loads

Having in mind the four studied design situations, previously considered for the tank modal analyses, four associated forced vibration dynamic structural analysis were performed on the structure, also including the prestressed effects. In this investigation, it was assumed that wind velocity can be divided into a static part and a turbulent part. The static part is usually obtained using the mean based on an interval of 10 minutes to 1 hour. On the other hand, the turbulent part was obtained based on the Spectral Representation Method (SMR) [11].

In this research work, the mathematical equation proposed by Kaimal was selected to model the power spectral density (PSD) of the wind longitudinal velocity associated to the turbulent part, considering different heights of the tank. The nondeterministic wind dynamic loads were developed based on the fluctuant wind parcel generated from the sum of a finite number of overlapping harmonics with random phase angles. The amplitude of each harmonic was obtained through the wind power spectral density [11].

The time responses for the Von Mises Stresses are illustrated in Fig. 5 and its maximum values are presented in Table 4. It is possible to notice that maximum values for the Von Mises Stresses on the tank are higher than the allowable stress values for the ASTM A 283 Gr. C steel plates (σ_{max} = 138 MPa), according to API 650 [2].

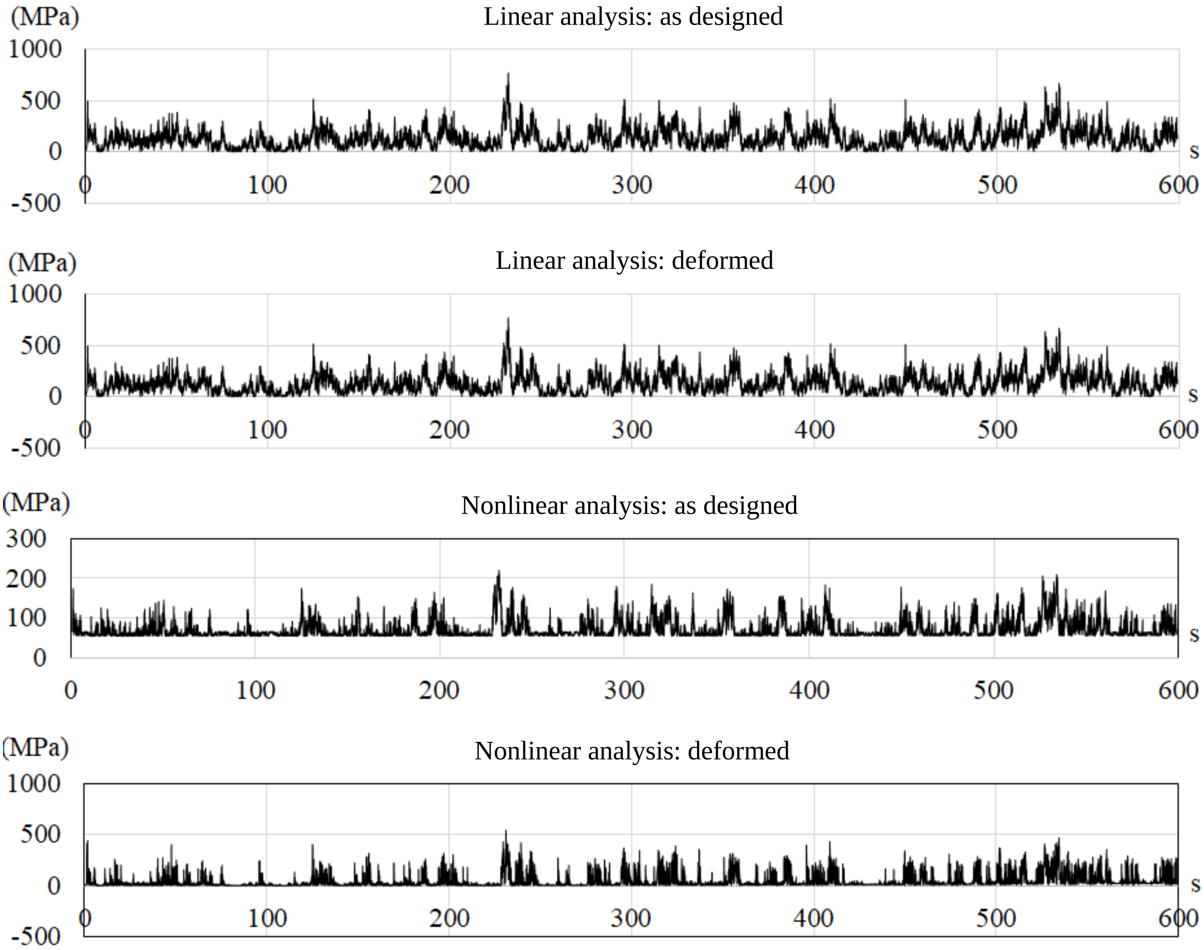

Figure 5. Von Mises stresses along the time.

Table 4. Maximum Von Mises stresses

Structural Analysis	σ_{max} (MPa)
Linear: as designed	772.93
Linear: deformed	816.24
Nonlinear: as designed	220.97
Nonlinear: deformed	545.05

6 Conclusions

The main conclusions of this research work are associated to the dynamic structural behaviour of a storage tank when subjected to nondeterministic wind loads whether as designed or deformed, based on the use of nonlinear finite element analyses, assisted by laser scan inspection techniques. Considering the obtained results, the developed analysis 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 practical for dimensional inspection.
2. The deformed structure modal analysis presented a much localized vibration mode shape vector. This behavior was quite expected, once the imperfections present in the shell of the tank can modify local stiffnesses of a highly deformed region, considering the thin cylindrical surface without any imperfections.
3. The non-deterministic transient analyses indicated that the allowable stresses for the ASTM A 283 Gr. C steel plates (σ_{max} = 138 MPa, according to API 650 [2]), have not been met.
4. The nonlinear effects considered for the forced vibration analyses of the investigated tank presented relevant differences when compared to the linear elastic analyses.

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