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Numerical evaluation on shell buckling of empty thin-walled steel tanks under wind load according to current American and European design codes

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ABSTRACT

Liquid storage steel tanks are vertical above-ground cylindrical shells and as typical thin-walled structures, they are very sensitive to buckling under wind loads, especially when they are empty or at low liquid level. Previous studies revealed discrepancies in buckling resistance of empty tanks between the design method proposed by the American Standard API 650 and the analytical formulas recommended by the European Standard EN1993-1-6 and EN1993-4-2. This study presents a comparison between the provisions of current design codes by performing all types of numerical buckling analyses recommended by Eurocodes (i.e. LBA-linear elastic bifurcation analysis, GNA-geometrically nonlinear elastic analysis of the perfect tank and GNIA-geometrically nonlinear elastic analysis of the imperfect tank). Such analyses are performed in order to evaluate the buckling resistance of two existing thin-walled steel tanks, with large diameters and variable wall thickness. In addition, a discussion is unfolded about the differences between computational and analytical methods and the conservatism that the latter method imposes. An influence study on the geometric imperfections and the boundary conditions is also conducted. Investigation on the boundary conditions at the foot of the tank highlights the sensitivity to the fixation of the vertical translational degree of freedom. Further, it is indicated that the imperfection magnitude recommended by the EN1993-1-6 is extremely unfavorable when applied to large diameter tanks. Comments and conclusions achieved could be helpful in order to evaluate the safety of the current design codes and shed more light towards the most accurate one.

1. Introduction

Above-ground, vertical tanks of cylindrical shape are constructed in industrial and agricultural plants to store various fluids such as petroleum, oil, fuel etc. They are welded, thin-walled structures with large diameters, and hence buckling may occur when they are subjected to wind loads at their empty or partially filled state. Failure of such tanks results, in most cases, in a tremendous loss of financial and human resources, as well as composes a threat to public safety and an environmental hazard. Studies concerning wind-induced buckling of steel tanks have been increasing over the past few decades, since structural stability becomes critical for response and a major concern for the designer.

Early studies approached this matter based on analytical formulations of energy theory and tried to verify results with experiments [1]. Following, numerical approaches have been conducted extensively, inserting the imperfection sensitivity parameter [2,3]. Different tank variations have been investigated, like open-topped [4] and fixed-roof [5–7], combining computational methods and experimental results. Jaca and Godoy [8] indicated that buckling of tanks sometimes can occur under moderate wind load during their construction. Another subject of interest is the wind buckling behavior of grouped, arranged tanks [9–11]. The simulation of wind load distribution acting on the tank shell is an open research field [12–14]. Innovative ways of strengthening and improving buckling capacity have been proposed [15]. Sosa and Godoy [16] and Burgos et al. [17] have recently taken a turn towards analytical methods, in order to improve buckling evaluation by proposing new methodologies.

This study aims to appraise the efficiency of current design specifications in addressing structural stability of empty, large tanks when subjected to wind actions. Most recent codes (EN1993-1-6 and EN1993-4-2) have not yet seen many field applications and their results may raise doubts. This paper offers a comparison between API 650 and the Eurocodes, by performing

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three types of buckling analysis recommended by the EN1993-1-6 for numerical investigation and relating the results with previous studies [18] conducted with analytical methods (closed-form, explicit expressions) proposed by the aforementioned codes. Thus, the stability of two existing large-diameter, steel tanks at empty state is evaluated.

The study is organized as follows: Section 2 describes the design philosophy of API 650 [19] and EN1993-1-6. In Section 3 the geometry of the two existing tanks is presented in detail and Section 4, presents the finite element models used for analyses and the wind pressures simulated for each code. Section 5 describes the linear bifurcation analysis (LBA) and in Sections 6 and 7 geometrically nonlinear buckling behavior is investigated for perfect (GNA) and imperfect (GNIA) models respectively. In Section 8 comparison results are discussed and finally in Section 9, some helpful conclusions are reached.

2. Description of current code provisions

The most commonly used standards for assessing the structural stability of thin-walled structures are the API 650 and EN1993-1-6. The American Standard API 650 provides two empirical methods (the one-foot method and the variable design point method) for selecting the thickness of each shell course, depending on the geometry of the tank, the operational liquid level, the material used, the density of the contained fluid and the allowance for corrosion. The aforementioned methods are based on the concept of limiting the tensile stresses of the shell due to hydrostatic pressure while they do not consider for buckling. The buckling limit state is considered only indirectly, via an empirical design method that mandates stiffening of the shell (with circumferential girders at specific heights) depending on the thickness, height and wind velocity. The lack of mathematical formulation for evaluating the shell stability poses a major disadvantage.

On the contrary, the European standard EN1993-1-6 [20] contains the theoretical background and provides the state-of-the-art methodologies for evaluating explicitly the buckling resistance of shell structures. Provisions include analytical expressions for calculating the buckling capacity in terms of stresses and also propose several numerical methods, like linear bifurcation analysis for obtaining the critical elastic buckling load as well as analyses that include geometrical and material nonlinearities and imperfections. Even though its provisions are limited to axisymmetric geometries, the European Standard has a wide range of applications with regard to cylindrical tanks. It is of paramount importance that the code quantifies the buckling resistance in terms of critical stresses or critical loads. An analytical procedure for evaluating the buckling resistance of shells with variable wall thickness has also been developed. Most of the approaches recommended by the European Standard require the use of computational methods, such as the finite element method, for analyzing the shell. The use of simplified expressions, according to basic principles of mechanics, for determining the design stresses is permitted only in certain cases. However, it should be highlighted that the European Standard is still very recent, and its applicability to the field construction has not been adequately confirmed up to date.

3. Geometry of the tanks

The two existing, thin-walled and large diameter steel tanks under investigation (T-776 and T-761) are shown in Fig. 1. They are located at the refinery of Motor Oil Hellas S.A. (Korinthos, Greece). Both tanks are cylindrical, self-supported (not anchored to the foundation), with flat bottoms and are considered empty. Tank T-776 supports a conical roof with a slope equal to 1/6, while the other tank is open-topped. The conical roof is supported by a truss structure with three groups of sections (L125x75 × 8, HEM1000 and SHS_80x80 × 8). The geometrical data of both tanks, including distinct locations of the ring stiffeners (wind girders) along the circumference, are presented in Table 1. It can be seen that the aspect ratio of tanks (H/D) is quite low (0.43 for T-776 and 0.22 for T-761).

Fig. 1. On-site pictures of tank T-776 (i) and tank T-761 (ii).

Table 1
Geometrical characteristics of tanks T-776 and T-761.

Tank ID	Shell Height (m)	Roof Height (m)	Inside Diameter (m)	1st Wind Girder Height* (m)	2nd Wind Girder Height* (m)
T-776	20.032	3.911	46.939	14.860	-
T-761	19.500	-	88.430	15.350	18.400

[*] Wind girder height is measured from the bottom of the tank.

Both tanks have variable wall thicknesses and their cylindrical shell is divided in nine courses. The width and thickness of each shell course along with relevant information regarding the bottom and roof (where applicable) are summarized in Table 2. The choice for the particular representative case studies is based on the variability of the geometric characteristics (aspect ratio, stiffeners, roof tops etc.) covering different structural behaviours observed in