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Hurricane failures of tanks for the oil industry

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Abstract

This paper presents an overview of recent research aimed at understanding the behavior of aboveground steel tanks under wind loads, carried out by the author and by other researchers in this field. The tanks considered are representative of those constructed for the oil industry, with radius to thickness ratios of the order of 1500, and height to radius ratios less than one. The paper discusses the buckling behavior of isolated tanks, and the buckling of tanks which are part of a group in a tank farm. The behavior of tanks with a fixed roof is shown with reference to failures occurred during the recent hurricanes in the Caribbean and the US Gulf. Finally, advances in modeling techniques are discussed, including computational buckling analysis and reduced stiffness methods.

Keywords: buckling, group effects, stability, steel shells, tanks, wind loads, wind tunnel tests

1. Introduction

Storage tanks are vital components in oil refineries and oil storage facilities. In a typical oil refinery, there is (a) an input area, i.e. the infrastructure that receives and stores raw materials, employing pipelines and tanks; (b) a process area, employing reactor towers, flare stacks, cooling towers to cool steam, and pipelines; and (c) an output area, where the finished fuels are stored in tanks with pipelines connecting them. Large ducts may also be part of the output.

Aboveground storage tanks are constructed in the form of a metal cylindrical shell with constant or tapered thickness, having (or not) reinforcing rings and a roof. Tanks have a flat, conical, or dome roof, although some have none. Floating roofs are usually provided to avoid dangers of vapor accumulation in the upper part on the inside of the tank. A dome roof is usually self supported, but conical and flat roofs need a system of columns and rings to avoid large deflections of the roof shell. A detailed description of tank components may be found in Myers [19].

The relative dimensions of oil tanks are very different from those employed in silos and other storage facilities. Short cantilever cylinders are commonly employed in large capacity tanks to store oil, with ratio R / H of the order of 2, and R / t of the order of 1000-2000, where R is the radius of the cylinder, H is the height of the tank, and t is the shell thickness. An illustration of tanks in a tank farm is shown in Figure 1.

The design of tanks follows API recommendations [1] in the US and Eurocode [3, 26, 27] in Europe. Because tanks are extremely thin-walled structures, wind is usually a primary design constraint. Failure of aboveground storage tanks under wind has been reported and investigated since the 1960s. Under hurricane winds, tanks may buckle with large deflections occurring in the windward area, as reported by the author and coworkers [8, 9, 10, 13, 24], among others. Such large deflections are of great concern to engineers, not only for their structural significance (which may eventually lead to a collapse), but also because the floating roof may cease to perform as designed. This causes the accumulation of vapor on top of the liquid and may lead to fire, as occurred in Guam in 2002.

Figure 1. Group of tanks in a tank farm, showing buckling of the central tank following Hurricane Georges in Yabucoa, Puerto Rico. (Photograph by the author)

This paper considers the buckling and post-buckling response of wind loaded, thin-walled cylindrical tanks, and the sensitivity of such buckling response to the influence of small geometric deviations from the cylindrical shape. The research reported here focuses on the short tanks employed to store oil, water, and petrochemical products in the Caribbean islands, in many parts of the United States, and in other geographical regions subject to high winds. There are two main areas of inquiry regarding wind buckling: one is the evaluation of pressures in tanks due to wind, and another is the structural evaluation of the shells due to wind. Although both could in principle be tackled as part of one model (i.e. wind tunnel testing of flexible structures), the current state of the art has been achieved by sequential investigations, in which the loads are evaluated first and they are subsequently considered as input in the structural analysis. Section 2 reviews some recent advances in the evaluation of wind pressures, whereas buckling is the subject of Section 3.

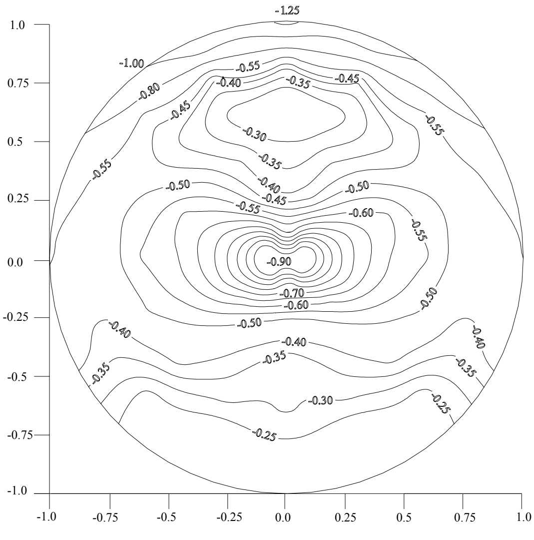
2. Wind and Hurricane Loads

Estimates of wind pressures in tank structures can be obtained using either physical or numerical simulations. Wind tunnel tests on small scale models are usually performed to evaluate pressure coefficients Cp by assuming that the structure is rigid. Numerical simulations are based on Computational Fluid Dynamics (CFD) software, in which the flow is represented in a domain of analysis that includes the structure as a boundary condition. There are two main configurations of interest: isolated tanks and tanks that are part of a group in a tank farm.

2.1. Pressures in isolated tanks

ASCE recommendations [2] suggest that wind pressures in a cylindrical structure should be assumed as uniform around the circumference. European recommendations [3] also give the possibility of representing wind acting on tanks by means of an equivalent uniform external pressure in order to perform hand calculations.

Most early data on circumferential pressure distributions due to wind are a consequence of adaptations of wind tunnel studies carried out for large cooling tower shells, which have very different aspect ratios than tanks. Resinger and Greiner [25], and Uematsu and Uchiyama [31], reported wind tunnel results for cylinders. Schmidt et al. [28] published post-buckling results from tests on PVC and steel cylinders under internal suction, and also under a static simulation of wind by means of a pressure that varies over segments of the shell; all cylinders included ring stiffeners on top, except for one case with H / R = 1 and R / t = 2,500, which was tested under internal pressure.



(a)

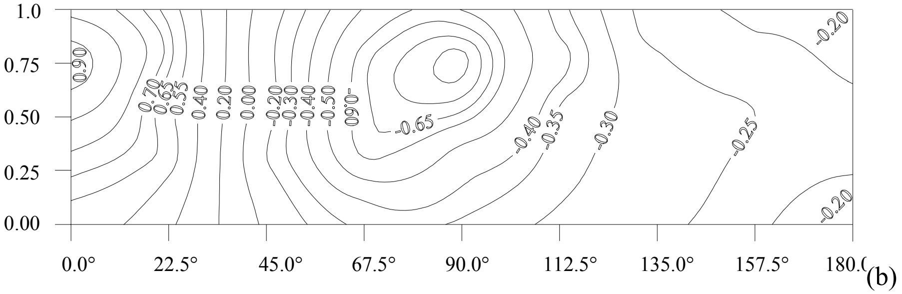


Figure 2. Cp values for a tank with conical roof (a) Cp on the roof; (b) Cp on the cylindrical part. Wind approaches from the top in Figure 2a, and at 0º in Figure 2b.

Recent wind tunnel tests on isolated tanks have been reported by Portela and Godoy for small scale tank models with conical [20] and dome roof [21] configurations. Small scale models were constructed using PVC, with relative dimensions H / D = 0.43, and Hr / H = 0.22, where D is the diameter and Hr is the height of the roof. Pressure taps were located in the meridional direction, and readings were made at meridians with angles of 22.5º in the circumferential direction. The results were summarized in the form of pressure coefficient (Cp) contours for the cylinder and the roof. An example of Cp contours is shown in Figure 2.

Empirical evidence shows that the aspect ratio of a tank greatly influences the values of pressure coefficients on the cylindrical part. For short tanks, i.e. H / D = 0.4 to 0.5, Cp values are lower than in tanks with H / D > 0.5. Positive pressures are detected in the windward area of the cylinder, with suction starting at approximately 90º from the windward meridian.

For tanks having a conical roof, only suction was obtained on the roof, with maximum values on the edge at the entrance of the flow. The abrupt change in the meridian between the cylinder and the roof induces a flow separation and high negative pressures on the roof. The angle of inclination of a conical roof is another relevant parameter that influences Cp values.

The shape of the tank at the transition between the cylinder and the roof significantly modifies the Cp values on the roof, because such details are responsible for the flow separation. The shallow dome roof has lower Cp values with respect to the conical roof, because it has a smooth transition.

Although fragmented because of the diversity of sources, there is at present reasonable empirical evidence derived from wind tunnel testing that can serve as the basis for further numerical studies. Such evidence is still to be incorporated in current design recommendation.

2.2. Tanks located in a hill

An illustration of CFD studies performed to evaluate Cp values in tanks is given by Falcinelli et al. [4], in which the influence of the location of a short tank in a hill is investigated (see Figure 3). The advantage of CFD over wind tunnel simulation in this case is that the domain would be too large for a wind tunnel to model wind and tank, but there are no such restrictions in the numerical simulation.

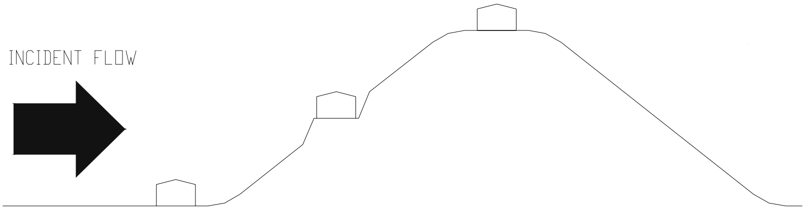


Figure 3. Locations of tanks in a hill investigated by Falcinelli et al. [4].

A hill obstructing the flow has a strong influence on the pressure profile affecting structures located in the hill. This was also predicted by the current ASCE provisions [2]; however, the conclusion of the CFD study indicate that the pressures depend on the specific geometry of the hill, including the dimensions and radius of curvature of the top flat part of the hill, and not just on the slope and height of the hill. Furthermore, the current provisions do not represent an upper bound to the pressures.

The actual location of the tank with respect to the hill has a large influence on the pressures acting on the tank. A tank located on top of a hill has pressure coefficients of the order of three times those acting on an isolated tank in flat terrain. For other locations at the base and mid-height of the hill, a decrease in pressure coefficients is observed with respect to the isolated tank. The reason for this is that the flow on the sides of the tank at mid-height of the hill has much less energy than in the isolated tank, because of the shielding effect produced by the flat surface on which the tank is supported. However, the maximum pressures in the windward meridian in the structure located at mid-height in the hill ($Cp = 0.94$) are larger than those in the isolated tank ($Cp = 0.75$), because there is no shielding for that part of the tank. Not just the values but the pressure distributions depend on the location. This shows that the results cannot be easily extrapolated for other topographic conditions, tank locations and sizes. Further research is needed in this area before general recommendations for design can be made.

2.3. Group effects in tank farms

Tanks in oil refineries and similar industrial facilities are seldom found in isolation and are grouped in various forms, according to the available land in the facility. Such arrangements may follow a regular pattern (i.e. tanks almost equally spaced in two directions) or in irregular arrangements, usually dictated by an initial pattern to which additions were made at a later stage, as in the tanks shown in Figure 1.

The ECCS TC8 recommendations (Rotter and Schmidt, [27]), show concern about the group effects in closely spaced similar structures. The evidence they used is a set of experiments carried out in 1974 by Vickery and Ansourian [32] to study a failure of six silos in New South Wales, Australia. The specific group configuration investigated by these authors is shown in Figure 4, in which wind approached the group from one side. For a closely spaced configuration of tanks with a roof, the tests led to a circumferential pressure variation having a more extended central angle of pressures in the windward zone. The consequence is that, for the same value of maximum pressures, the loads acting on a central angle of about 160 degrees leads to different modes and loads of buckling.

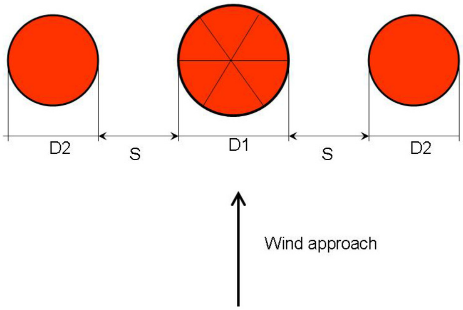


Figure 4: Group configuration investigated by Vickery and Ansourian [32], with D1 = D2.

Table 1: Cases of groups of tanks investigated at the University of Puerto Rico, with D1 = 30.48m. Maximum pressure λ ×1 KPa.

Case	H1/D1 conical	H2/D2 Flat roof	H1/H2	S	λ
1	0.43	0.43	1	D1	4.78
2	0.43	0.43	1	0.5 D1	3.97
3	0.43	0.30	1	D1	3.43
4	0.43	0.30	1	0.5 D1	2.70
5	0.60	0.30	2	0.5 D1	2.44
6	0.43	0.68	1.4	0.13 D1	3.38
7	0.43	0.39	1.43	D2	3.11
8	0.43	0.39	1.43	0.5 D2	2.84
9	0.43				2.43
10	0.43				2.61

The study of groups of tanks at UPR emphasized the identification of pressures in tanks that are not in the front row facing wind; i.e. the specific configurations are representative of tanks that are shielded by others. Details of the configurations considered at UPR are shown in Table 1 and Figure 5. The first five cases in Table 1 (Figure 5a) are formed by two tanks with diameters D1 = D2 (cases 1 and 2) or D2 = 0.7 D1 (cases 3 and 4) with separation S = D1 (cases 1 and 3) or S = 0.5 D1 (cases 2 and 4). Case 5 is similar to case 4 but with a taller tank D1. In case 6 a small tank is placed in front of a larger one. Cases 7 and 8 are formed by three tanks, as illustrated in Figure 5b. Finally, cases 9 and 10 are representative of the groups of tanks shown in Figure 1.

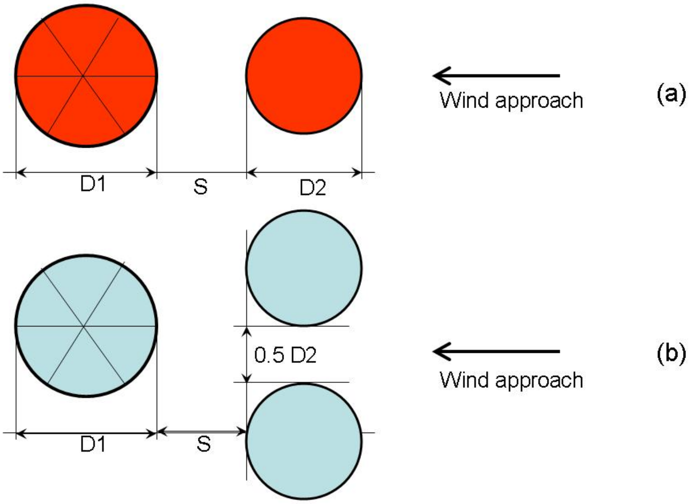


Figure 5. Two configurations of group of tanks investigated at UPR [22, 23]: (a) Two tanks, cases 1 to 6 in Table 1; (b) Three tanks, cases 7 and 8 in Table 1.

For tandem arrays, a tank in front of another blocks the flow and reduces the pressures in certain zones of the second tank in line. But one cannot state that tanks in a second row will always be in favorable conditions with respect to tanks in the first row, because the pressures depend on the relative dimensions between D1 H1 and D2 H2. If the first tank is significantly shorter than the second one, then there is a flow separation from the roof in the first tank that affects the second one with high localized pressures. Pressure increases of the order of 20% were reported by Portela and Godoy [22]. Another consequence is the presence of asymmetric pressure distributions which may no longer be coincident with the global wind direction.

More complex groups of tanks are representative of a specific configuration, as considered by Portela and Godoy [23]. Depending on the array, there are significant changes in pressure distributions with respect to the isolated tank, involving differences in the maximum Cp values. Drops in maximum Cp were obtained for case 9 in both windward and leeward regions. Most important for the buckling behavior is the actual location of the maximum Cp in height at the highest loaded meridian, which occurs at a lower elevation than in isolated tanks. Values on the roof increase close to the junction with the cylinder but are reduced at the center.

3. Buckling of tanks

A sequential experimental/computational approach has been followed by the author and coworkers in order to uncouple the evaluation of loads from the stability studies. Thus, the values of Cp identified in the previous section were employed to assess buckling loads and modes in tanks, which can be compared with evidence of damage in real structures under hurricane winds.

Regarding buckling estimates, most computational studies use linear elastic bifurcation (denoted as LBA in the European recommendations [27]), geometrically nonlinear elastic analysis (GNA), or geometrically nonlinear elastic analysis with imperfections (GNIA). Isolated tanks with a roof display bifurcation-type behavior, with an initially stable equilibrium path computed with NGA followed by an unstable nonlinear response in the post-critical path (Flores and Godoy [5]).

3.1. Buckling of isolated tanks

The literature on the buckling of cantilever cylindrical shells under wind load has mainly concentrated on tanks or similar structures that are not short. The computational research in this field includes the work of Schmidt et al. [28], who explored design strategies based on the use of ring stiffeners as a way of preventing global buckling (i.e., buckling modes that have large displacements around the top edge). Their design recommendations are supported by computational results limited to perfect cylindrical shells. Greiner and Derler [15] included the influence of imperfections using different patterns for the shape of the geometric deviation. For short shells, it was found that imperfection sensitivity was highest for imperfections with the shape of the eigenmode associated to the lowest bifurcation load.

It was shown in the previous section that there is a complex pressure pattern due to wind, with changes from positive to negative pressures as one considers meridians from windward to leeward. To understand the behavior of tanks with roof under wind gusts, it was initially assumed that it was necessary to consider dynamic buckling. However, natural periods are sufficiently apart from wind gust excitation, as shown by Virella et al. [33].The results reported by Godoy and co-workers [6, 7, 14, 29] show that inertia forces do not play an active role and that this is essentially a static problem.

The maximum load that a tank can sustain in a stable configuration does not seem to be so sensitive to the precise pressure pattern. The computational experiments carried out by the author and coworkers using NGA and ABAQUS [17] indicate that the maximum loads in tanks with conical roofs are only marginally affected by the negative pressure distribution around the tank or by the precise pressure distribution along the meridian. Buckling is dominantly induced by the local positive pressures in the windward region, and changes in the buckling mode (rather than in buckling load) are noticed as different models of leeward suction are considered (Flores and Godoy [6], Godoy and Mendez [12]).

The influence of the roof on the buckling behavior has two opposite effects: first, there is an additional stiffness provided by the roof (preventing large horizontal displacements), and second, there is an additional surface of the structure on which suctions occur.

Regarding imperfection sensitivity, it was found that 25% reductions are expected as imperfections in the geometry of the order of the thickness are included in the model (Godoy and Flores [11]).

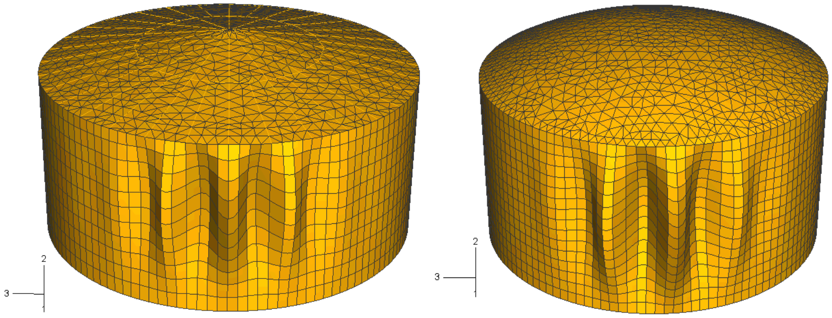


Figure 6. Buckling modes for tanks with (a) conical roof; (b) shallow dome roof.

3.2. Buckling of tanks in tank farms

It is not simple to summarize results from groups of tanks, because critical loads depend on Cp values, which in turn are obtained for a specific group configuration. For tandem arrays with equal height tanks, buckling loads are higher than in isolated tanks because of shielding. However, buckling loads are reduced if the maximum positive pressures acting on the shell were separated enough from the cylinder-roof transition, which in turn depends on the relative height between the tanks in the first and second line facing wind. Thus, a short tank shielding a taller one may have flow separation that impacts the second tank with high localized pressures leading to low buckling loads.

For irregular groups of tanks, such as in the case shown in Figure 1, the buckling load resulted in a slight decrease with respect to the isolated tank. However, the imperfection sensitivity in the group of tanks was found to be less pronounced than in the single tank.

4. Areas of further research

This paper attempted to illustrate the complexities present in studies aimed at understanding the buckling behavior and damage of thin-walled tanks under wind. Two main fields are involved in this problem: First, the evaluation of wind loads, and second, the computation of realistic buckling or damage loads.

In the first case, one needs to identify the typical geometries and group arrangements that are found in a given area before a complete plan of current needs is defined. Understanding typical configurations can be obtained from an inventory of tanks for the area of interest; this task has been performed by Virella et al. [34] for Puerto Rico, and would be required for other regions for which reasonable buckling estimates are needed. This characterization of geometries is also needed if fragility or vulnerability curves are required by a stakeholder interested in assessing the potential cost due to a hurricane, such as governments (to estimate future investments) or insurance companies (to estimate insurance policy prices). Other needs in this field are the evaluation of Cp values for tanks in special locations, such as those constructed inside a dike.

It was mentioned that current buckling estimates are performed using LBA, GNA or GNIA finite element analysis. An alternative methodology to estimate lower bound buckling loads is the Reduced Stiffness Method (or Reduced Energy Method), which is based on the elimination of some energy contributions in the shell. This method has been employed by Sosa et al. [30] and Jaca et al. [18] in recent years, with excellent results. The advantage is that it does not require performing GNIA studies and the lower bound buckling loads are obtained from LBA analyses. Again, this is an excellent technique if large number of cases are required, such as in the computation of fragility curves.

Other failure modes have been identified during hurricanes: During Hurricane Katrina, tank dikes in oil storage facilities in the New Orleans region were flooded and detached from their base [10]. Those tanks floated and produced oil spills, with infrastructure as well as legal costs. Research into this failure condition is required in order to prevent damage to the tank and to the environment.

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