BUCKLING OF ABOVEGROUND STORAGE TANKS WITH CONICAL ROOF

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ABSTRACT

The buckling of aboveground circular steel tanks with conical roof is considered in this paper. The specific source of loads investigated is wind action during hurricane storms in the Caribbean islands. The structure is modeled using a finite element discretization with the computer package ALGOR. Bifurcation buckling of the shell is computed for a given static wind pressure distribution. Then the bifurcation loads and buckling modes are compared with the evidence of real tanks that failed during hurricane Georges in Puerto Rico in 1998. Several pressure distributions are assumed for the roof of the tank, and it is shown that the results are highly sensitive to the choice of pressures.

KEYWORDS

ALGOR, Bifurcation analysis, buckling, finite elements, hurricane winds, metal tanks, mode shape, shells, wind pressures.

INTRODUCTION

The failure of tanks employed to store water and oil in the Caribbean Islands has been studied in recent years by the first author. Buckling of aboveground circular steel tanks with and without a roof was observed in St. Croix in 1990 (hurricane Hugo), St. Thomas in 1995 (hurricane Marilyn), and in Puerto Rico in 1998 (hurricane Georges). For tanks without a roof, or for those that lost the roof before the cylindrical part buckled, it was possible to reproduce the expected behavior using computer modeling. For example, a tank without a roof that failed in St. Thomas was modeled using standard wind pressured distributions around the circumference (Flores & Godoy 1997). For such a pressure, the computer model displays buckling for the wind speeds usually found during a hurricane. However, a far more difficult job is faced in an attempt to model the failure of the cylindrical shell in a tank with a conical roof or a shallow dome. The main questions regarding the pressure distributions on the roof are not answered within the current state of the art. In this paper we employ computer modeling to identify adequate pressure distributions that are compatible with the structural evidence showing buckling due to hurricane winds.
The search for adequate modeling of loads due to natural hazards is of great importance for the prediction of the safety of structures. There are various ways in which this is done at present. On the experimental side one can perform a full-scale test on a real structure or instrument it until an event occurs. The use of small-scale models is another possibility. Computer modeling of the environmental action on the structure is now possible, specially thanks to advances in Computational Fluid Dynamics. And there is the possibility of linking the failure of uninstrumented structures to the loads that led to their failure. This work explores the last possibility within the context of tanks exposed to hurricanes winds.

For tanks with a roof (either conical, spherical, or flat), the literature on wind load buckling reduces to a few contributions. Some extensive books on the design of tanks (Myers 1997, Ghali 1979) do not consider buckling under wind load. Early studies in the 1960s on the wind pressures on cylinders with shallow cap roofs were reported by Maher (1966), while an extension for flat roof was published by Purdy, Maher & Frederick (1967). The literature on silos may also be relevant for short tanks; however the aspect ratio of tanks (height to diameter) of interest in this work is of the order of 1/5, while for silos this is higher than 1. Esslinger, Ahmed & Schroeder (1971) investigated silos with a dome roof under wind. This work is also discussed by Greiner (1998). Other wind tunnel tests were performed by Resinger & Greiner (1982), but there is no information about pressure distributions on the roof. The influence of group effects in silos under wind was reported by Rotter, Trahair & Ansourian (1980) from buckling experiments in a wind tunnel. The silos tested were aligned in a single row perpendicular to the direction of the wind, and closely spaced. Esslinger, Ahmed & Schroeder (1971) tested two cylinders with spherical cap roof separated by a distance of the order of a diameter, and for various directions of wind incidence. For two tanks aligned in the direction of the wind, the first tank shelters the second one, and develops pressures on the windward side, suction close to 90 degrees from the wind direction, and small pressures on the leeward side. The roof has suction on a small part of the windward side, and pressure on the leeward side. Such non-uniform pressure distribution on the roof is also found for other orientations of wind. The influence of an internal operating vacuum may further modify the wind pressures.

Flores and Godoy (1997) studied the nonlinear dynamic response of short tanks and found that inertia effects were not significant in this class of shells, so that static analysis could well be carried out to estimate instability under wind load. In the following sections we describe the computational finite element model employed and consider a specific structure to investigate its buckling failure. Several pressure distributions are assumed for the roof and the results of buckling pressure and mode shape are compared with the evidence from real cases.

**COMPUTATIONAL MODEL**

A metal circular tank with a conical roof under a static pressure distribution (Figure 1) is modeled in this paper in order to evaluate bifurcation buckling loads and modes. Because there is evidence that the real tank failed during hurricane Georges in Puerto Rico, then we have an upper limit to the wind velocity at the time of buckling. The buckling mode observed in the real tank includes plasticity effects associated to an advanced post buckling behavior; however, the localization of the mode at the windward meridian and the mode shape are considered similar to the initiating elastic buckling mode. Preliminary studies using geometrically nonlinear analysis indicate that instability in this case has small displacements in the pre buckling equilibrium states and that the maximum load and mode attained by the tank are well represented by a bifurcation study. This is by no means a general conclusion and applies only for the geometry of the tanks considered, which is rather short. At least for open tanks, it has been shown (Godoy & Flores 2000) that the aspect ratio and thickness slenderness are crucial to determine the type of instability that may be found in the structure.
The general purpose finite element package ALGOR (1999) was employed to build the computational model using 2250 shell elements, including 1250 quadrilateral elements for the cylinder and 1000 elements (either quadrilateral or triangular) for the roof. The boundary conditions at the bottom of the shell are assumed as clamped. Only one-half of the tanks is modeled, with symmetry in the plane of incidence of wind. The mesh of elements is shown in Figure 2.

A series of bifurcation buckling analysis were made in order to identify adequate pressure distributions on the roof, which are compatible with the evidence observed in real structures. This was accomplished by calculating the critical bifurcation buckling mode and pressure and comparing them with the maximum load expected to occur during a hurricane.

CASE STUDIED

The theme structure in this paper is a tank with variable thickness, as shown in Figure 1. The tank has 30.5 m of diameter and a height of 12.2 m. It is made of steel with the assumed properties listed in Table 1. The tank is located in Peñuelas, an industrial area in the south of Puerto Rico, where a large number of tanks were build in order to store petrochemical products for the many industrial companies that developed several years ago.

<table>
<thead>
<tr>
<th>Properties of the tank</th>
<th></th>
</tr>
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<tbody>
<tr>
<td>Radius</td>
<td>15.24 m</td>
</tr>
<tr>
<td>Height</td>
<td>12.192 m</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>$2.068 \times 10^{11} \text{ N/m}^2$</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.3</td>
</tr>
<tr>
<td>Mass density</td>
<td>7849.7 kg/m$^3$</td>
</tr>
<tr>
<td>Yield stress</td>
<td>$2.156 \times 10^8 \text{ N/m}^2$</td>
</tr>
</tbody>
</table>

This tank was damaged by winds during hurricane Georges in 1998, as shown in Figure 3. The tank was empty at the time when the hurricane hit the area; it belongs to a group of tanks that are separated by a distance of approximately 50 m, and its location is close to the coast (about 300 m from the coast).
ASSUMED PRESSURE DISTRIBUTIONS

It was assumed that the pressure distribution around the circumference has positive values on the windward meridian, and negative pressure (suction) on the rest of the cylinder, and was modeled as a constant unit pressure in the vertical direction. This pressure pattern was used by many authors before (ACI-ASCE 1991, Flores & Godoy 1998, 1999).

In order to propose a pressure distribution for the roof of the tank we used the photographs as a guide to how the tank buckled under wind load. For this purpose we used an inverse technique of cause and effect, in which the photographs showed the effect of the hurricane winds. Once the buckling mode shape was available, we attempted to find the pressures that caused this failure. Several bifurcation buckling analyses were made using ALGOR for different pressure distributions on the roof. Then the buckling load was calculated for each case. Every load assumption used caused a different buckling load and mode shape in the structure. Finally, we searched for a buckling load similar to the load expected during a hurricane that caused a buckling shape similar to the one photographed just after the hurricane occurred.

RESULTS FOR DIFFERENT PRESSURE DISTRIBUTIONS ON THE ROOF

In Load Case 1 the tank was modeled by taking the influence of the roof with upper boundary conditions instead of the roof itself. This class of models is attractive because one does not model the roof with finite elements, but it neglects the pressures that may act on the roof surface. First, the cylindrical tank clamped at the top was considered. This lead to a buckling mode consistent with what was observed in the structure, but for a high load factor of \( \lambda_c = 3.35 \text{ kN/m}^2 \) (or wind speed of \( v = 66.9 \text{ m/s} \)). For a simply supported condition on top, the values changed to \( \lambda_c = 3.33 \text{ kN/m}^2 \). This model shows a buckling mode shape similar to the real mode. For a free condition at the top it is not expected that the model simulates a roof, and is only considered here as a reference case. The load factor changed to \( \lambda_c = 1.3605 \text{ kN/m}^2 \), but the mode shape from such computations was very different to the one expected.

Load Case 2: In order to include the influence of the roof into the model we assumed different patterns of wind pressures acting on the roof. As a first option, we included a downward constant pressure as a percentage of the maximum pressure (1 kN/m\(^2\) ) applied on the walls. The distribution of pressure (ACI-ASCE, 1991) applied around the circumference has a maximum value of 1 kN/m\(^2\). For this load
case we obtained the results plotted in Figure 4. The buckling mode of each of these cases was very similar to the real one, as shown in Figure 5.

Load Case 3 was a variable pressure load acting on the roof. It was assumed that the meridian of the shell has pressures with the same sign, and following a circumferential distribution similar to a tank without a roof. This pressure load on the roof has the same orientation as the pressures acting on the walls, and we call this a “variable pressure” because it varies in the circumferential direction. The magnitude of the pressures varies according to the direction with respect to the incidence of the winds. The positive pressures produce a downward pressure on the roof, while negative magnitudes of pressure produce an upward pressure (suction). The scope of this analysis was the same as in Load Case 2, varying the percentage of the pressure load to study the variation of the critical load, Figure 6. In this case the critical buckling loads were very high, exceeding the expected range.

Load Case 4: Consultations with wind-experts led to the recommendation that an upward pressure should be present, following the experience with pressures on buildings with rectangular plan. For this case we applied a constant upward (negative) pressure to the roof. In this model only suction occurs on the roof. With full maximum constant pressure (1kN/m²) acting upward on the roof the buckling load was -2.98 kN/m². With 90% of the maximum constant pressure acting the buckling load was –1.83 kN/m². Negative values of critical buckling load mean that the pressure distribution should be applied in the opposite direction. The buckling mode for this case was very interesting: The roof suffered large buckling deflections instead of the walls, and the buckling mode shows a totally different shape, Figure 7. This shape is far from what is observed in the real situation.
Load Case 5: Wind-tunnel experiments in Germany (Esslinger, Ahmed & Schroeder 1971) have shown that for silos, the pressure on a conical roof is negative on the windward part of the roof and positive on the leeward part. At the center of the conical roof the pressures are zero, and they take non-zero values on a ring which spans half way between the center and the edge of cone. Our cases 5 and 6 take that into account. For Load Case 5 we applied a variable pressure but with the “inverse orientation” of the pressure acting on the walls (Greiner, 1998). That means that the roof is modeled with positive pressure in the places where the wind is negative on the walls, and negative (suction) pressure in the places where the walls have positive pressures. The critical buckling loads are similar to the expected load corresponding to the wind speed measured for the area in which the tanks are built. The variations of the critical load due to the increase of variable pressure load are plotted in Figure 8. Notice that this behavior is similar to what was obtained for Load Case 2. Furthermore, the modes of buckling computed were also similar to those expected in comparison with the photographs (Figure 9).

![Figure 8. Load Case 5.](image1)

![Figure 9. Load Case 5.](image2)

![Figure 10. Load Case 6.](image3)

Load Case 6: We assumed that the pressure acting on the wall only affect some part of the roof. In this case the pressure was applied over the circumference of the roof to a distance of one fourth of the diameter of the roof measured from the corner (the junction between the roof and the wall). This distribution left the middle section of the roof without any pressure. The orientation of the load was the same assumed for the Load Case 5. The critical load computed by ALGOR was 3.03 kN/m². The buckling mode shape for this case is also similar to those obtained from Load Cases 2 and 5. The buckling mode shape corresponding to this distribution is shown in Figure 10.
DISCUSSION

For the first load case (Load Case 1) the tank was modeled using three different boundary conditions instead of the roof. For the tank clamped at the top the buckling load was larger than the expected range of values (wind speed larger than that registered in the area in which the tank is built), although the buckling mode shape was similar to the one expected. The same situation occurred with the tank modeled with a simply supported condition at the top. For a free condition at the top the buckling load was smaller than the other two cases but the buckling mode shape was totally different of the one expected.

In Load Case 2, a downward constant pressure was applied on the roof. The results obtained vary depending on the magnitude of the pressure used. As discussed before, the magnitudes considered vary in percentages of the maximum constant pressure (1kN/m²). For 50% up to 120% of the maximum constant pressure the critical buckling load resulted in values very close to the one expected. These values decrease as the percent of full pressure acting on the roof increases. The estimated range of the velocity pressure for an open area is between 2.40 kN/m² and 3.00 kN/m², corresponding to wind velocities from 56 m/s up to 67 m/s (125 mph up to 150 mph). The values between 10% and 40% lead to high wind speeds. In terms of the buckling mode shape, the results obtained for the different magnitudes of pressure were similar to the shape expected according to the photographic evidence.

For Load Case 3, in which the applied load was a variable pressure acting on the roof, the results were not satisfactory in terms of the buckling load. That means that if we applied on the roof a distribution that varies according to the direction of winds (positive pressures on the cylinder produce a downward pressure on the roof, while negative magnitudes of pressure on the cylinder produce an upward pressure on the roof) we obtain very large values of the critical buckling load. These values also changed the sign if we increase the pressure to more than 50% of the value of the pressure on the cylinder. Such pressure distribution is not recommended in this context.

For Load Case 4 (constant upward pressure on the roof) we obtained negative values of buckling load, which means that the distribution used in this case was not satisfactory. This case considers also the distribution used on the walls, and for this reason this is not a good distribution to model the wind. The buckling mode shape obtained was very different from the one expected, i.e. the tank model failed in the roof instead of the walls.

In Load Case 5 we applied a variable pressure distribution but with the inverse orientation of the pressure acting on the walls (Esslinger, Ahmed & Schroeder 1971, Greiner 1998). The critical buckling load computed in this case was similar to that computed in Load Case 2 and the results are also satisfactory. The modes of buckling were also similar to those obtained for Load Case 2.

For Load Case 6, which is a variation of Load Case 5, we obtained a critical buckling load just larger than the one obtained for the 100% of the load in Load Case 5. The value was over the expected range, but very close to the maximum load expected. The buckling mode shape was similar to those modes obtained for load cases 2 and 5.

CONCLUSIONS

The pressures distributions obtained for silo structures with shallow cap roof by Esslinger and coworkers (1971) seem to be an adequate representation for short tanks with conical roof. In this case the pressure distribution on the roof is not uniform, but has suction close to the meridian of incidence of wind, and positive pressure on the leeward side of the shell, while the central part of the roof does not have pressures. For such pressure distributions the buckling pressure (and associated wind velocities)
and the buckling mode shape were consistent with those found in the field following hurricane Georges in 1998.

This preliminary study illustrates the sensitivity of the buckling response with the pressure distribution assumed on the roof. More detailed experimental evidence of pressure distributions for short tanks is required, and this could be obtained from wind-tunnel experiments. Such studies are now being performed at the University of Puerto Rico at Mayagüez.

ACKNOWLEDGEMENTS

This work was sponsored by the US National Science Foundation (NSF) under grant CMS-9907440, and by the US Federal Emergency Management Administration (FEMA) under grant PR-0060-A. The support of both institutions is greatly appreciated.

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