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Review

Buckling of vertical oil storage steel tanks: Review of static buckling studies

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ABSTRACT

Research on the structural behavior and buckling of vertical, aboveground tanks employed to store oil and fuels have significantly increased during the past two decades. Interest in this shell form is related not just to the cost of the infrastructure, but also because failures in cases of accidents or natural disasters may cause huge economic, environmental and social losses. This review concentrates on buckling problems of such tanks under static or quasi-static loads, including uniform pressure, wind, settlement of foundation, and fire. In all cases, buckling is considered as a static process. Attention is given to the load definition in each case, followed by buckling studies under previously defined pressures or temperatures. The structural configuration of tanks is first described in order to understand what is specific about this structural form. Next, the theoretical framework for stability and buckling is briefly described to place each contribution in a wider context. Each loading case is first explained, experiments or case-studies are briefly described, and computational analytical modeling is reviewed; finally, efforts towards improving design are mentioned. Most papers published in the literature have been motivated by wind effects on tanks, but the review shows that other areas, such as thermal buckling under an adjacent fire, are currently receiving increasing attention.

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1. Introduction

Vertical aboveground tanks are employed in several industries to store water, oil, fuel, chemicals, and other fluids. Depending on the specific industry and on the fluid stored, different materials are employed in the fabrication of tanks: in the oil industry, metals have been used almost exclusively. Basically oil tanks are thin-walled short cantilever shells, and have geometrical and structural differences with other storage shells, such as silos or pressure vessels which tend to be taller. Oil storage tanks are constructed using curved steel sheets, commonly known as courses, with dimensions depending on the local steel industry, and which are welded together to form the cylinder. Because of their geometric slenderness, tanks are prone to fail by buckling, and frequently this failure initiates in a form of elastic buckling.

Considerations about buckling of tanks under various loading conditions should not be restricted to new designs, because most tanks employed at present were fabricated before the 1980 s and efforts are continuously made to extend their service life in order to avoid interruptions in the operation of a plant. Recently there is a trend to fabricate new tanks which are increasingly larger and thinner than old ones [126], with the consequence that they have geometries which are more slender than those used in the aerospace or in the off-shore industries.

There have been several reviews of shell buckling which may be related to this one. The most influential review of computational buckling analysis of shells was published by Bushnell in 1981 [25] as a summary to his book on the topic. The aim in Bushnell's work was to provide a large number of illustrative examples in order to foster a feeling for buckling behavior in engineers. Emphasis was on understanding buckling by intuition rather than from theoretical formulations. By means of carefully chosen examples, Bushnell illustrated cases in which eigenvalue bifurcation analysis provides inadequate information; effects due to boundary conditions, nonlinearity in the fundamental equilibrium path, plasticity, mode interaction; and problems in which deep knowledge is required in order to fully understand the behavior in design or in a failure investigation. Because many shell forms and applications were covered in Ref. [25], Bushnell could bring experience to illustrate a wide variety of unstable behavior. However, the possibilities of nonlinear behavior and buckling are considerably reduced when one specifies a shell configuration, as in the present case.

A thorough review paper on shell buckling by Teng [161] was published in 1996. Teng and Rotter [162] compiled a book on buckling of metal shells. A review of the developments of stability of shells in the XX Century was written by Elishakoff [43]. Thompson has recently revisited his views on the mechanics of shell buckling from the perspective of bifurcation and chaos [164].

Schmidt [153] summarized work on shell buckling research that was subsequently adopted in the European Recommendations [147]. Failure modes in silos and tanks have been summarized by Rotter [144,146], with emphasis on silos. Recently, Zingoni [187] published a comprehensive review of strength, stability and dynamics of tanks, including vertical and horizontal designs, as well as tanks used to store water which are supported by a central column. This is the closest review to the present one, but because a wider scope of tank configurations and mechanics of behavior were considered by Zingoni, only his Section 2 overlaps with the present review.

Many buckling problems in steel oil or fuel storage tanks may be modeled as a quasi-static problem, including the buckling under uniform external pressure, wind load, thermal loads, and foundation settlement, and those are reviewed in this paper. Dynamic buckling problems arise under time-dependent loads due to earthquakes and suddenly applied loads associated with explosions, and require using dynamic buckling criteria to assess the stability of the shell; those are not considered in this paper.

In all cases reviewed in this paper there is a sequential analysis, in the sense that pressures are evaluated at a first stage (either from lab tests or from computer simulations) and the structural response under such pressures is computed at a second stage.

2. Structural configuration of tanks

A summary of the main characteristics of tanks as fabricated for the oil industry is given in this section; further details are given in books on tanks, such as Myers [121] and Refs. [54,40]. Design recommendations are given in Refs. [7,20,45], among others. Comparisons of design methods for tank thicknesses acceptable to API standards [7] are reported by Azzuni and Guzei [11].

Oil storage tanks are fabricated with a cylindrical shell having a stepped thickness with a bottom circular plate at the base and some form of roof at the top. Less frequently, there are some small tanks fabricated with uniform thickness. There are two main classes of roof: a fixed roof welded to the cylinder, or a floating roof; however, some tanks have both a fixed roof on top and a floating roof inside.

The buckling strength of the cylindrical shell of tanks largely depends on two geometric parameters: the aspect ratio, as defined by the ratio between the height H and the diameter D of the cylinder (H/D), and the slenderness (R/t) calculated as the ratio between the radius R of the shell and its minimum thickness t. As mentioned before, tanks fabricated with a rather short cantilever cylinder with $1{,}000 < R/t < 2{,}000$, and $H/D < 1$. Diameters have been increased in the recent decade, in a trend to build fewer tanks with larger capacity. Increasing sizes are reported in China, reaching D = 100 m, with volumes of fluid storage in the order of 100,000m^3 [186]. Similar trends are informed in France, with tanks reaching D = 80 m; to illustrate different sizes, volume capacities have been classified as 100,000m^3, 10,000m^3, and 1,000m^3 [125]. An increase in volume capacity is accompanied by an increase in D and a decrease in the aspect ratio H/D.

Because results for one tank geometry may not be directly applicable to other geometric configurations, then care is taken in