Thin-Walled Structures 79 (2014) 83–94

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Buckling of cylindrical open-topped steel tanks under wind load

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ARTICLE INFO

Article history:
Received 7 December 2013
Received in revised form
6 February 2014
Accepted 11 February 2014
Available online 28 February 2014

Keywords:
Buckling
Steel tanks
Wind load
Open-topped
Imperfection sensitivity
Wind girder

ABSTRACT

Vertical cylindrical welded steel tanks are typical thin-walled structures which are very susceptible to buckling under wind load. This paper investigates the buckling behavior of open-topped steel tanks under wind load by finite element simulation. The analyses cover six common practical tanks with volumes of $2 \times 10^3\,\text{m}^3$ to $100 \times 10^3\,\text{m}^3$ and height-to-diameter ratios $H/D < 1$. The linear elastic bifurcation analyses are first carried out to examine the general buckling behavior of tanks under wind load, together with comparison to that of tanks under uniform pressure and windward positive pressure (only loaded by positive wind pressure in the windward region). The results show that for larger tanks in practical engineering, the stability carrying capacity of wind load is relatively lower. It is also indicated that the buckling behavior of tanks under wind load is governed by the windward positive pressure while wind pressure in other region of tank essentially has no influence on the buckling performance. The geometrically nonlinear analyses are then conducted to investigate the more realistic buckling behavior of tanks under wind load. It is found that the buckling behaviors of perfect tanks and imperfect tanks are much different. The weld induced imperfection only has little influence on the wind buckling behavior while the classical buckling mode imperfection has significant influence, leading to a considerable reduction of wind buckling resistance. The influences of thickness reduction of cylindrical wall, liquid stored in the tank and wind girder on the buckling behavior are also examined. It shows that the thickness reduction of cylindrical wall considerably reduces the wind buckling resistance while sufficient liquid stored in the tank and wind girder significantly increase the wind buckling resistance.

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1. Introduction

Vertical cylindrical welded steel tanks are widely used for fluid and bulk storage in industrial and agricultural plants. They usually consist of a thin bottom plate, a cylindrical shell with uniform or stepped thickness and a closed-roof or open-top (with or without floating roof) [1]. The typical structure of cylindrical open-topped steel tanks is shown in Fig. 1. With the development of economy and oil industry, more and more oil storage tanks are put into service in recent decades, especially large tanks. Some tanks even have diameter larger than 100 m, with volumes of more than $100 \times 10^3\,\text{m}^3$. Fig. 2 shows steel tanks in practical engineering.

As typical thin-walled structures, tanks are very susceptible to buckling under wind load especially when they are empty or partially filled. Over the past few decades, buckling failures of cylindrical steel tanks and silos during windstorm have occurred in many countries and regions [2–4]. Buckling of tanks sometimes even occurs under moderate wind load during their construction [5]. Because of serious economic losses and environmental problems due to the destruction of storage tanks, studies about buckling of tanks under wind load have been conducted extensively over the past few decades.

Kundurpi et al. [6] studied the buckling behavior of open-topped cylindrical tanks due to wind load based on the energy theory and compared with experimental evidence. It was shown that the engineering practice of determining buckling load was conservative. Uematsu and Uchiyama [7] investigated the buckling behavior of closed-ended, thin cylindrical shells by wind-tunnel tests. They found that the buckling load was not sensitive to the wind pressure distribution and the buckling behavior exhibited a pronounced non-linearity. An empirical formula for the buckling pressure considering the height/radius ratio and the radius/thickness ratio was also proposed by them. Greiner and Derler [8] performed numerical analyses on the wind buckling of cylindrical shells considering several different imperfection shapes. It was found that the longer cylinders were most sensitive to local rectangular or ring shape imperfections while stocky cylinders were more sensitive to global eigenmode-shaped imperfections. Schmidt et al. [9] carried out tests on both PVC and steel cylinder models under a “wind-like” load to study the post-buckling phenomena and provided some design recommendations

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http://dx.doi.org/10.1016/j.tws.2014.02.010
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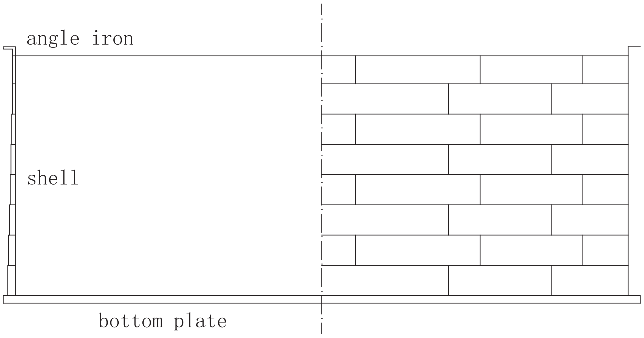

Fig. 1. Typical structure of open-topped steel tanks.

Fig. 2. Steel tanks in practical engineering.

based on the experimental results. Flores and Godoy investigated the buckling behavior of short cylindrical shells subject to strong wind load by numerical approach, in which models were representative of tanks devastated during hurricane Marilyn in the Caribbean islands. Portela and Godoy [10,11] addressed the buckling of steel tanks with a conical or dome roof due to wind load, in which the imperfection sensitivity was examined through geometrically nonlinear analyses. They also investigated open-topped tanks using the same cylindrical wall model and wind load to confirm the roof effect on the buckling behavior of cylindrical tanks. Jaca et al. [12] adopted a reduced stiffness approach for evaluating the lower bound of buckling of open-top cylindrical tanks under wind load based on reduced energy model. They found that results obtained from reduced stiffness approach constituted a lower bound to those obtained from numerical analyses as well as experiments. Further work had been performed by Sosa and Godoy [13] and Jaca and Godoy [14], which put the method into a wider application. Jaca and Godoy [5] noticed that wind-induced damage of tanks occurred not only during windstorm but also under moderate wind load during their construction. They tried to reveal the mechanism of collapse through geometrically nonlinear analyses. This work was also carried out by Borgersen and Yazdani [15], in which some design recommendations and construction methods to prevent failure during construction were given. Chen and Rotter [16] performed analyses on the buckling of anchor cylindrical shells due to wind pressure with focus on the uniform thickness cylinders, covering a wide range of tanks with different aspect ratios. Zhao et al. [17] investigated the buckling behavior of steel silos subject to wind pressure through a great deal of numerical analyses, which aimed to improve the understanding of buckling behavior of large circular steel silos subject to wind pressure. It was indicated that the buckling resistance of steel silo was closely correlative with loading conditions as well as geometrical parameters.

From literature reviewed above, it can be found that few studies have been conducted on the buckling behavior of practical open-topped steel tanks with stepped wall when they are subject to wind load including internal pressure.

This paper covers six common practical open-topped tanks with volumes of $2\times10^3\ \mathrm{m}^3$ to $100\times10^3\ \mathrm{m}^3$ and aspect ratios (height-to-diameter) $H/D<1$. The internal pressure due to wind is included in present study. The following three types of buckling analyses recommended by EN 1993-1-6 [18] are performed for numerical investigation: (a) LBA—linear elastic bifurcation analysis of the perfect tank; (b) GNA—geometrically nonlinear elastic analysis of the perfect tank; (c) GNIA—geometrically nonlinear elastic analysis of the imperfect tank.

The layout is organized as follows: Section 2 expatiates upon the structure prototypes of six tanks, the finite element models used for analyses and the wind pressures on both external and internal wall of tank. Section 3 presents the linear elastic buckling behavior of tanks under wind load, together with comparison to that of tanks under uniform pressure and windward positive pressure (only loaded by positive wind pressure in the windward region). Geometrically nonlinear buckling behavior is investigated in Section 4, using perfect and imperfect models. The influences of the thickness reduction of cylindrical wall, the liquid stored in tank and the wind girder on the buckling behavior are examined and discussed in Section 5. Finally, some valuable conclusions are drawn in Section 6.

2. Computational models

2.1. Structure prototypes

Table 1 summarizes the geometries of tanks TK1–TK6, which are representative of six common practical tanks with volumes of $100\times10^3\ \mathrm{m}^3$, $50\times10^3\ \mathrm{m}^3$, $20\times10^3\ \mathrm{m}^3$, $10\times10^3\ \mathrm{m}^3$, $5\times10^3\ \mathrm{m}^3$, $2\times10^3\ \mathrm{m}^3$, correspondingly. These six types of tanks are constructed extensively not only in China but also in other countries [19]. The structure of cylindrical shell and the dimensions (in mm) of shell courses for each tank are summarized in Table 2. Data of these tanks refers to practical engineering and some reasonable simplifications are made for analyses. It can be seen that as the volume increases, the aspect ratio H/D decreases while the average thickness of cylindrical shell increases. Fig. 3 shows the relative sizes of different tanks.

2.2. Finite element model

The finite element package ABAQUS is employed to carry out the analyses. The 8-node, quadrilateral, first-order interpolation, stress/displacement continuum shell element with reduced integration S8R5 is chosen to discretize the cylindrical wall. This element has 5 degrees of freedom per node: translations in the nodal x, y, and z directions and rotations about the nodal x, and y-axes, which is more economical in comparison to that using six degrees of freedom [20]. The fixed boundary condition (Ux, Uy, Uz, $Rotx$, $Roty$, $Rotz=0$) is applied on the bottom of the FE model. The material of cylindrical shell is assumed to be isotropic elastic with

Table 1
Geometries of tanks.

	TK1	TK2	TK3	TK4	TK5	TK6
H (m)	21.8	19.35	15.85	15.85	14.27	12.69
D (m)	80	60	40.5	28.5	22	14.5
H/D	0.27	0.32	0.39	0.56	0.65	0.88
V (m^3)	100,000	50,000	20,000	10,000	5000	2000

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