Full length article

Effects of wind girders on the buckling of open-topped storage tanks under quasi-static wind loading

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A R T I C L E   I N F O

Keywords:
Storage tank
Open-top
Wind girder
Wind tunnel experiment
Wind pressure distribution
Finite element analysis
Buckling

A B S T R A C T

The present paper investigates the wind resistant design of ring-stiffened open-topped storage tanks based on finite element analyses, in which we use the distributions of wind pressure on isolated and grouped tank models measured in a wind tunnel experiment. The effects of top/intermediate wind girders on the buckling load and mode of tank shells are investigated based on the results of buckling analysis for quasi-static wind loadings. The design recommendations for the wind girders are proposed, which may provide more reasonable design criteria for the wind girders than the current design guidelines.

1. Introduction

Storage tanks are generally composed of thin curved steel panels. Buckling may occur when they are subjected to wind loads in the empty or partially-filled state (see Refs. [1,2] for example). For open-topped tanks, buckling may occur more easily than closed-topped tanks due to the effect of larger negative internal pressures, generating larger net wind forces on the windward area of tank shells; internal pressure refers to the wind pressure acting on the internal surface. Even in the case of closed-topped tanks, similar damage may occur when the tank is under construction and the roof has not been fixed yet [3]. Therefore, wind-induced buckling is one of the most important technological problems for the engineers, when designing and constructing these tanks. Wind girders (stiffening rings) are often installed at the top and, if necessary, in the upper part of the tank to improve the wind resistance.

Many researchers extensively studied the wind-induced buckling of thin cylindrical structures in the 1970s and 1980s (e.g. Refs. [4–11]). In most cases, they dealt with closed-topped cylinders and carried out wind tunnel experiments in smooth uniform flows. The distributions of mean wind pressure coefficients obtained from such wind tunnel experiments were used for investigating the buckling behavior of cylindrical structures.

With an advance in finite element method (FEM) together with a remarkable development of computers after the late 1980s, many researchers conducted buckling and post-buckling analyses of wind-loaded cylindrical shells using FEM (e.g. Refs. [12–20]). Among them, Bu and Qian [18,19] and Lewandowski et al. [20] investigated the effect of intermediate wind girders on the buckling of thin-walled steel tanks under static wind loading. These studies dealt with closed-topped cylinders and used simplified models of wind pressure coefficient distributions cited from code provisions and/or previous studies.

Wind pressure distributions on isolated and grouped tanks with flat and conical roofs were measured in a turbulent boundary layer by Macdonald et al. [21–23]. Recently, Portela and Godoy [24–27] and Burgos et al. [28] measured the distributions of mean external pressure coefficients $C_{pe}$ on isolated and grouped tanks with various roof configurations (i.e. flat, conical and domed) and analyzed the buckling of cylindrical steel tanks using the wind tunnel data. Sosa and Godoy [29] and Burgos et al. [30] proposed simplified methods to estimate the buckling loads of tank shells and wind girders.

Most of the previous studies, including the above-mentioned ones, investigated the aerodynamics of closed-topped tanks. However, open-topped tanks with floating roofs are often used at oil storage bases. Such tanks are more sensitive to wind loading due to the effect of internal pressures, generating larger net wind forces on the windward area of the tank shell. The earliest study on the wind resistance of open-topped oil storage tanks was made by Holroyd [31,32], who computed the dynamic response of tanks based on a frequency domain analysis and suggested that the structural vibrations might play a significant role in initial buckling failure of tank shells. Uematsu and Koo [33] investigated the characteristics of wind pressures on closed-topped and open-topped cylinders with aspect ratios $(H/D)$, with $D$ and $H$ being the...
diameter and height of tank (m, respectively) of 0.5–3 in a turbulent boundary layer. The effects of aspect ratio on the external and internal pressure distributions were discussed. Godoy and Flores [34] analyzed the imperfection sensitivity to elastic buckling of open-topped cylindrical tanks under static wind loading. Because the tank model used in their analysis was not stiffened by wind girder at the top, the model was not practical.

Buckling of isolated and/or grouped open-topped storage tanks were investigated by Jaca et al. [35], Yasunaga et al. [36–38], Zhao and Lin [39], Zhao et al. [40] and Uematsu et al. [41,42]. Yasunaga et al. made a simultaneous measurement of fluctuating wind pressures at many points on the external and internal surfaces of open-topped tank models [36–38]. To the authors’ best knowledge, this is the first extensive measurement of fluctuating wind pressures on open-topped tanks. They investigated the dynamic characteristics of wind pressures using a conditional sampling technique, POD analysis (Proper Orthogonal Decomposition analysis) in order to investigate the structure of wind pressure field; regarding the details of this analysis, see Bienkiewicz et al. [43], for example. It was found that the instantaneous wind force distribution at an instant when the external pressure coefficient at the windward stagnation point became the maximum peak value was similar to that of the mean wind force coefficient $C_{f,mean}$ provided by the difference between the mean external and mean internal pressure coefficients, particularly in the windward area. This feature implies that the wind force coefficient for designing open-topped storage tanks can be estimated based on the distribution of mean wind force coefficients. Furthermore, they indicated that the buckling behavior of storage tanks under static wind loading was governed by the windward positive pressure, while wind pressure in the other region of tank had little effect on the buckling. Almost the same result was reported by Zhao et al. later [39]. Yasunaga et al. [37,38] and Uematsu et al. [41,42] proposed models of design wind force coefficients for open-topped storage tanks, based on the wind pressure measurements in a turbulent boundary layer as well as on the buckling test and analysis with elastic tank models. In their analysis, the wind girder at the top was assumed rigid.

Very recently, a critical review of wind buckling of thin-walled tanks has been presented by Godoy [44].

The present paper investigates the buckling of ring-stiffened open-topped storage tanks under wind loading based on finite element analyses. Because the API Standard 650 [45] is often used for designing oil storage tanks in Japan, the criteria for designing the wind girders in the Standard is first reviewed in the present paper. Then, the fundamental characteristics of buckling of open-topped storage tanks with rigid top wind girders are investigated. The distributions of mean wind force coefficient $C_{f,mean}$ measured in a turbulent boundary layer are used in the analysis. A brief explanation of the wind tunnel experiment with isolated and grouped tank models is also presented. Two or three identical models in in-line arrangement are used in the wind tunnel experiment. Note that the purpose of this wind tunnel experiment with grouped models is not to discuss the interference effect of grouped tanks on the wind pressure distribution but to obtain various wind force coefficient distributions for discussing the effect of wind force distribution on the buckling of tanks; the results for the distributions of wind pressure and force coefficients on isolated and grouped tanks are described in Yasunaga et al. [37,38]. Next, the effects of flexural and torsional rigidities of the top and intermediate wind girders on the buckling are investigated. A criterion is proposed for the flexural rigidity required for the wind girders that increases the buckling load most effectively. An empirical formula is also provided for the buckling load of ring-stiffened storage tanks. Then, the stresses induced in the wind girders are analyzed theoretically. Based on the results together with those of the buckling analysis, a design criterion is proposed for the wind girders.

It should be mentioned that the present paper is an extended version of our recent papers (Yamaguchi et al. [46], Uematsu et al. [47], Yasunaga et al. [48,49]). The design criteria for the top/intermediate wind girders are discussed in more detail.

2. Requirements for wind girders specified in the API Standard 650

According to the API Standard 650 [45], which is often used for designing oil storage tanks in Japan, the value of section modulus $Z_{top}$ (cm$^3$) required for the top wind girder is calculated by the following equation:

$$Z_{top} = \frac{D^2H}{17} \left( \frac{V}{190} \right)^2$$  \hspace{1cm} (1)

where $D$ and $H$ represent the diameter and height of tank (m); and $V$ is the design wind speed represented by 3-s gust wind speed (km/h). When the height $H$ is larger than the maximum height $H_1$ (m) of the unstiffened tank wall, defined by Eq. (2), intermediate wind girders shall be installed so that the distance between wind girders becomes smaller than $H_1$:

$$H_1 = 9.47 \sqrt{\left( \frac{D}{190} \right)^3 \left( \frac{V}{190} \right)^2}$$  \hspace{1cm} (2)

where $t$ represents the thickness of tank (mm). When the wall thickness changes stepwise, $H$ is replaced by an equivalent height $H_E$ (m) defined by the following equations:

$$H_E = \sum_{i=1}^{N} W_{Ei}$$  \hspace{1cm} (3)

$$W_{Ei} = W_i \left( \frac{t_{min}}{t_i} \right)^2$$  \hspace{1cm} (4)

where $N$ is the total number of layers that consist of the tank wall; $W_i$ and $t_i$ represent the height (m) and thickness (mm) of the $i$-th layer, respectively; and $t_{min}$ is the minimum wall thickness (mm). The section modulus $Z_{tanks}$ (cm$^3$) required for the intermediate wind girders is given by the following equation:

$$Z_{tanks} = \frac{D^2H}{17} \left( \frac{V}{190} \right)^2$$  \hspace{1cm} (5)

The above-mentioned specifications are based on the buckling of thin cylindrical shells under uniform lateral load. In practice, however, the distribution of the net wind force, provided by the difference between the pressures on the outside and inside (‘external’ and ‘internal’) surfaces of the tank, is far from uniform and depends on the aspect ratio $H/D$ of tank as well as on the turbulence characteristics of approach flow.

3. Wind tunnel experiment of wind pressure distributions on tanks

3.1. Experimental apparatus and procedure

The experiment was carried out in a closed-circuit-type wind tunnel at Kajima Technical Research Institute, which has a working section 18.1 m long, 2.5 m wide and 2.0 m high. A turbulent boundary layer with a power law exponent of 0.15 for the mean wind speed profile was generated on the wind tunnel floor. The details of the wind tunnel experiment are described in Uematsu et al. [42]. Three rigid models (named ‘A’, ‘B’ and ‘C’) with aspect ratios $H/D$ of 1.0, 0.5 and 0.25 were used for measuring the wind pressures on the external and internal surfaces (external and internal pressures). The external diameter $D$ and wall thickness of the models were 250 mm and 6 mm, respectively. Although the wall is much thicker than that of practical tanks, its effects on the external and internal pressures seem minimal. The geometric scale of the models was assumed 1/400, which was nearly equal to that of the wind-tunnel flow on the basis of the length scale of turbulence.
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