Thin-Walled Structures 92 (2015) 76–81

Contents lists available at ScienceDirect

Thin-Walled Structures

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

A rational design approach of intermediate wind girders on large storage tanks

Fan Bu *, Caifu Qian

Beijing University of Chemical Technology, Beijing 100029, China

ARTICLE INFO

Article history:
Received 5 January 2015
Received in revised form
13 February 2015
Accepted 20 February 2015
Available online 17 March 2015

Keywords:
Large storage tank
Intermediate wind girder
Wind load
Tank bottom
Finite element analysis
Buckling

ABSTRACT

In storage tanks, intermediate wind girders are used to prevent the buckling failure of tank wall caused by wind load. For the design of the intermediate wind girders, two key parameters must be determined: the size of intermediate wind girders and the spacing between the girders. In the code API650, the spacing is expressed as the maximum height of the unstiffened tank wall and the size is referred to the minimum section modulus. In this paper, the design approach for the maximum height of the unstiffened tank wall and the simplified mechanical model for the minimum section modulus adopted in API650 were presented to reveal the simplification regarding the magnitude and action zone of wind load and the negligence of the strengthening effects of the tank bottom. A 3D finite element model was built to study the wind pressure distribution around the tank and strengthening effects of the tank bottom. Optimal analysis to minimize the weight of the wind girders for a given wind load was performed numerically and formulas for the size and spacing of the wind girders according to the optimal results were given. Based on the optimal design proposed in this paper, the material consumed for the winder girders were significantly reduced.

1. Introduction

Large oil storage tanks are more and more widely used in petro and petro-chemical industries. A major failure form of the large storage tanks is the buckling of the tank wall under wind load. Therefore, stiffening rings are usually needed to strengthen the tank wall. Among them, intermediate wind girders play a key role in the safe and reliable operation of tanks. Regarding the design of intermediate wind girders, some engineering design approaches were specified in codes and some studies were addressed especially about the simulation and simplification of the wind pressures acting on the tanks, the constraint conditions at the bottom of the tank wall and the buckling behavior of the tank wall.

It is stipulated in API650 that an open-top tank shall be provided with stiffening rings to maintain roundness when the tank is subjected to wind loads [1]. Gong et al. performed an analysis of a large storage tank subjected to the wind load. They found that for the tank under static wind pressure, the maximum displacement occurs on the tank wall close to the top edge, where wind girders should be located [2]. Uematsu et al. carried out a series of wind tunnel experiments on large storage tanks. They found the failures of tanks are mainly caused by the positive wind load on the windward side and the mean distribution of wind pressure, more easily measured than the instantaneous distribution, could be used for the design of tank [3]. The wind pressure distribution around vertical cylindrical storage tank has been studied extensively. Li and Tse put forward an approach, based on the turbulent kinetic Energy Dissipation Rate, to estimate the turbulence intensity of wind load through the use of a turbulent length scale model. Based on this approach, strong wind above the height of 10 m from the ground can be measured exactly [4]. Through the experiment on a reduced scale model in a wind-tunnel simulation, Holroyd found the principal features of wind pressure distribution around the tank wall and put forward some indications to improve the distribution. Besides, necessary steps and research to get a new criterion, based on this distribution, for calculating the wind speed at which tanks failed were discussed [5,6]. By studying the circular cylinders with stiffening rings through wind tunnel tests, Lupi et al. found the existence of a new type of bistable flow, induced by the stiffening rings, around the circular cylinders with a free-end [7]. Chen and Rotter derived the stresses of stiffening ring on tank using a linear shell bending theory. They proposed a new rational approach to calculate both the precise membrane and the bending stresses of different kinds of unsymmetrical stiffening rings [8]. Gong et al. performed an finite element analysis of open top tanks. Their results indicated that the structure parameters of top stiffening rings, including the length and the thickness, play a significant role on the failure of the tank [9]. Briassoulis and Pecknoid performed an analysis of three empty stiffened steel silos with different heights under wind load. It was pointed out that an oversized wind girder makes no sense due to the large circumferential stress resulting from the composite action

* Corresponding author.
E-mail address: wileam0326@163.com (F. Bu).

http://dx.doi.org/10.1016/j.tws.2015.02.024
0263-8231/

between the tank wall and the wind girder [10]. The stresses of tank wall and wind girders are also in connection with the constraint condition at the bottom of tank wall. Jaca and Godoy performed finite element analysis on the buckling of storage tanks under wind load. The results indicated that the incomplete junction with the bottom plate must be taken into account in the explanation of the failure mechanism [11]. Zhao et al. analyzed the tanks with circumferential differential settlements by means of the geometrical nonlinearity algorithm. The results indicated that for tanks under global differential settlement, local failure occurs first at the top wind girder, so the local failure of wind girders could be taken as the service ability limit state [12]. By studying the stresses of the tank wall and wind girders, Topkaya and Rotter proposed a new chart to predict the maximum shell membrane stress caused by circumferential differential settlements. They pointed out that differential settlements had an adverse effect on the membrane stress of tank wall [13]. By studying the buckling of tanks under the uniform pressure and the wind pressure, Zhao and Lin found that the anti-buckling capacity of tanks under wind load is relatively lower. The results also indicated that the buckling behavior of tanks under wind load was governed by the windward positive pressure while wind pressure in other region of tank essentially had no influence on the buckling performance [14]. Jaca et al. proposed a lower bound approach to the buckling analysis of cylindrical shells for tanks subjected to wind load and pointed out that the resulting critical loads constituted lower bounds to those obtained from experiments [15]. Portela and Godoy performed an experimental and computational study to evaluate the buckling behavior of steel tanks with dome roofs and conical roofs. They found that buckling occurred in the form of deflections in the cylindrical shell and the buckling mode was localized in the windward region. Besides, the tanks showed low sensitivity on the geometrical imperfections [16,17]. Lei and Michael performed a study on the anti-buckling capacity of large tanks under wind and proposed an empirical expression to relate the linear critical stagnation pressures to the classical critical value for uniform external pressure [18].

2. Design approach of intermediate wind girders in API650

Intermediate wind girders are used to prevent the buckling failure of tank wall under wind load, thus they should be designed based on buckling theory [19,20]. For the design of intermediate wind girders, two key parameters must be determined: the spacing and the size of wind girders. In the code API650, the spacing is expressed as the maximum height of the unstiffened tank wall (MHUTW) and the size is referred to the minimum section modulus (MSM). The design approach of MHUTW and MSM is introduced in the following part.

2.1. Design of MHUTW

Due to the thin-walled structure of the tank wall, elastic buckling may occur on the tank wall under wind load. Thus in API650, the MHUTS is designed according to the linear buckling theory with a safety factor of 3.0. The critical pressure of the tank wall, a typical short cylinder, can be calculated by the following formula:

$$P_s = \frac{Et_{s\ \min}^{2.5}}{4.56 \times 10^4 H_{TS} D^{1.5}} \tag{1}$$

where P_s = total design external pressure, kPa, E = modulus of elasticity of the material, MPa, $t_{S\min}$ = minimum thickness of tank wall, mm, H_{TS} = MHUTW, m, D = nominal tank diameter, m.

According to formula (1), with wind load expressed as the design wind speed, the MHUTW should be:

$$H_{API} = 2.64 \times 10^4 t^{2.5} D^{-1.5} V^{-2} \tag{2}$$

where V = design wind speed, m/s.

2.2. Design of MSM

Since the circumferential stress is the dominant stress on the tank wall under wind load, the other stress components are ignored. The maximum circumferential stress should not exceed the allowable stress, and thus, the MSM is determined. Regarding the MSM, the design approach of intermediate wind girders is the same with that of top wind girder except the difference of the bearing range in the height direction.

The wind load is considered to vary circumferentially but remains constant in the height direction in API650. The maximum average wind velocity lasting 3 s in 50 years is taken as the design wind speed expressing the value of wind load. It is assumed that 120 mi an hour wind produces 30 psf of flat area and that a cylinder has a shape factor of 0.6 producing an effective pressure of 18 psf of projected area on a cylinder, where the air density is taken as 1 kg/m^3 [21]. The wind loads on the upper part are assumed to be born by the wind girder, or in other words, strengthening effects of the tank wall and other structures are ignored. Thus, the minimum section modulus can be derived with a two-dimensional (2D) model.

The simplified mechanical model of the tank under wind load is shown in Fig. 1. Only the windward side of the tank wall is under the action of wind load. Being symmetrical about the stagnation point, the wind load distributes in a cosine function and reaches the maximum value ω_0 at the stagnation point. The direction of wind load is perpendicular to the tank wall at the stagnation point, and at other positions, wind load also remains in this direction. The projection of the wind load on the diameter perpendicular to the wind load is a uniform pressure with a value of ω_0. The tank wall is constrained not only at one point, but at all the positions in the circumferential direction. The reaction force distributes in a sine function symmetrical about the stagnation point and reaches the maximum value of $2\omega_0/\pi$ at the position of 90° and 270°. The direction of the reaction load is tangential to the tank wall. As a weighted combination of the Case 1, Case 8 and Case 18 in Fig. 2, the model can be solved by Roark's ring cases [22]. In US customary units, the bending moment should be:

$$M = CwR^2 \tag{3}$$

where M = bending moment, lb ft, C = coefficients in Table 1, w = wind load in unit length, lb/ft, R = radius of the ring, ft.

The maximum bending moment occurs at the stagnation point. With coefficients listed Table 1, the maximum bending moment should be:

$$M = 0.00877 D^2 H \omega_0 \tag{4}$$

where D = nominal tank diameter, ft, H = height of the tank wall, ft, ω_0 = basic wind pressure, psf.

According to formula (4), the MSM in SI units should be:

$$Z_{API} = 2.11 \times 10^{-5} D^2 HV^2 \tag{5}$$

where Z_{API} = minimum section modulus, cm^3.

The formula (5) can also be used in the design of intermediate wind girders when the H represents not the height of the tank wall, but the MHUTW. With the substitution of formula (2), the

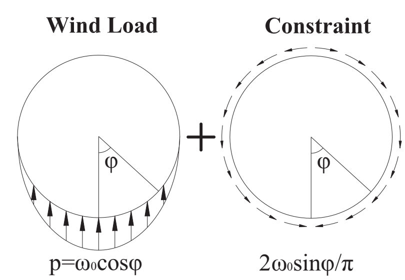

Fig. 1. Schematic diagram of the simplified mechanical model in API650.