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On the rational design of the top wind girder of large storage tanks

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ABSTRACT

In this paper, simplified mechanical models for the design of the top wind girder of large storage tanks adopted in the codes SH3046 and API650 were presented to show their differences regarding the wind load magnitude and action zone. Finite element models for the tanks were built to study the strengthening effects of the bottom constraints. It is found that for a large storage tank with a small ratio of height to diameter, the strengthening effects of the bottom constraints are significant and should not be ignored. If based on two-dimensional models without considering the strengthening effects of the bottom constraints, the strength design of the top wind girder according to the present codes of SH3046 or API650 is too conservative.

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 insufficient stiffness of the tank wall under wind loads. Therefore, stiffening rings are usually needed to strengthen the tank wall. Top wind girder is the one which is placed near the top of the tank and plays a key role in the safe and reliable operation of tanks. Regarding the design of the top wind girder, some engineering design approaches are specified in codes and many studies were addressed especially about the simulation and simplification of the wind pressures acting on the tanks and the constraint conditions at the bottom 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. The stiffening rings shall be located at or near the top of the top course, preferably on the outside of the tank shell [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 the top wind girder 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 a method, 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 method, 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 method to determine both the precise membrane and the bending stresses of different kinds of unsymmetrical stiffening rings [8]. Gong et al. performed a 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 the wind load. It was pointed out that an oversized top wind girder is impractical due to the large circumferential stress resulting from the composite action between tank shell and wind girder [10]. The stresses of tank shell and wind girder are also in connection with the constraint condition at the bottom of tank shell. Zhao et al. analyzed the tanks with circumferential differential settlements by means of the geometrical nonlinearity algorithm. The results indicated that local failure occurs first at the top wind girder for tanks under global differential

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settlement. Thus the ability of the wind girder to resist buckling could be taken as the bearing capacity of the whole tank [11,12]. By studying the stresses in the tank shell and the top wind girder, Topkaya and Rotter proposed a new design chart to predict the maximum shell membrane stress caused by different kinds of settlements. They pointed out that differential settlements had an adverse effect on the membrane stress of tank shell [13].

2. Design methods of the top wind girder in codes

The top wind girder must have sufficient stiffness to resist wind loads. The required minimum section modulus is given in the Chinese code SH3046 and American code API650 as listed in Table 1. The wind load is expressed as the basic wind pressure in SH3046 and as the design wind speed in API650. The two parameters, with no essential difference, can be transformed into each other by:

$$\omega_0 = \frac{\gamma V^2}{2} \tag{1}$$

where ω_0 = basic wind pressure, Pa,
γ = density of air, kg/m^3,
V = design wind speed, m/s.

Regarding the calculation of the required minimum section modulus, differences are found between the two codes mainly in three points: (1) the values of wind load together with the correlated factors, (2) the allowable stresses of materials, (3) the simplified mechanical models. In SH3046, the maximum average wind velocity of 10 minutes in 50 years is taken as the design wind speed. However, in API650, the maximum average wind velocity of 3 seconds in 50 years, 1.44 times the value in SH3046, is taken as the design wind speed. The correlated factors applied in the two codes are listed in Table 2. The allowable stress is 0.9 times the yield strength (about 210 MPa) in SH3046 while that is 0.625 times the yield strength (about 146 MPa) in API650. The differences between the simplified mechanical models are discussed in the following sections.

3. Simplified mechanical models

Both the design methods in the two codes are based on the buckling theory, but should be calculated through strength methods [15,16]. Since the circumferential stress is the dominant stress at the tank shell under the wind load, the other stress components are ignored. The maximum circumferential stress should not exceed the allowable stress, and thus, the required minimum section modulus are determined. The wind load is considered to vary circumferentially but remains constant along the height in the two codes. The wind loads on the upper part are assumed to be borne by the wind girder, or in other words, strengthening effects of the tank shell and other structures are ignored. Thus, the required minimum section modulus can be derived with a two-dimensional model as presented below.

Table 1
Formulas for calculating required minimum section modulus in codes.

Codes	Formulas for calculating required minimum section modulus
SH3046	$W_{zk} = 8.3 \times 10^{-11} D^2 H \omega_0$ [14]
API650	$W_{zk} = 5.882 \times 10^{-8} D^2 H (\frac{V}{52.8})^2$ [1]

Notes: W_{zk} = required minimum section modulus, m^3,
D = nominal tank diameter, m,
H = height of the tank shell, m.

Table 2
Correlated factors applied in codes.

Name	SH3046	API650
Wind vibration factor	1.5 [15]	1.1
Height vibration factor	1.15 [15]	1.1
Shape factor	0.64 [16]	0.6 [17]
Loads bearing range	0.5H [16]	0.25H [17]

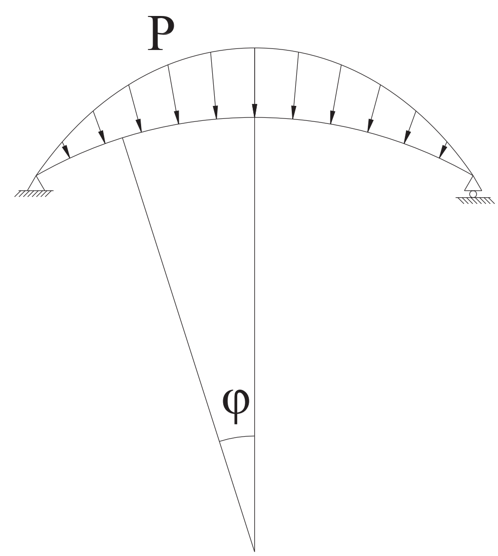

Fig. 1. Schematic diagram of the simplified mechanical model in SH3046.

3.1. Simplified mechanical model in SH3046

In SH3046, the tank shell at the windward side in a circumferential range of 60° (namely wind zone) with symmetry about the stagnation point is assumed to take the wind load as shown in Fig. 1. In addition, the wind load is distributed in the form of a cosine function [15,17]. Using the correlated factors in Table 2, the distributed function is:

$$p = p_0 \cos 3\varphi = 0.32 H \omega_0 \cos 3\varphi \tag{2}$$

where p = wind load in unit arc, Pa m,
p_0 = wind load in unit arc at the stagnation point, Pa m,
φ = circumferential angle to the stagnation point, rad.

The tank shell in other 300° range (namely windless zone) is omitted both the structure and wind loading. So the top wind girder can be regarded as a curved beam carrying vertical load. The constraint of the windless zone is reflected by a fixed hinge support at the left side and a sliding hinge support at the right side. With such supports, the displacement in wind load direction is zero at the beam ends, while the other displacements and rotations are unconstrained.

The maximum bending moment derived by Institute of Mechanics, Chinese Academy of Sciences is adopted in SH3046 [18], which is:

$$M = 0.125 p_0 r^2 = 0.01 D^2 H \omega_0 \tag{3}$$

where r = tank radius, m.

Based on formula (3), the required minimum section modulus in SH3046 is:

$$W_{zk} = 8.21 \times 10^{-11} D^2 H \omega_0 \tag{4}$$

It should be pointed out that the effect of windless zone is hard