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Design wind force coefficients for open-topped oil storage tanks focusing on the wind-induced buckling

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ABSTRACT

Wind force coefficients for designing open-topped oil storage tanks have been investigated both experimentally and analytically. First, simultaneous pressure measurements were carried out at many points both on the outside and inside of the wall of a rigid model in a turbulent boundary layer. A conditional sampling of pressures was made for investigating the pressure distribution at an instant when the external pressure at a reference point, roughly corresponding to the windward stagnation point, became the maximum peak value. The instantaneous distribution of wind force coefficients, or the pressure difference coefficients at this moment was found to be similar to that of the mean wind force coefficients. Then, the buckling behavior of thin cylindrical shells was investigated based on a wind tunnel experiment with elastic cylinders. Furthermore, a finite element analysis of the buckling behavior under static wind loading was carried out. The results indicate that the buckling behavior is mainly affected by the magnitude and extent of positive wind force coefficient on the windward area of the cylinder. Finally, a discussion is made of the wind force coefficients to be used for the design of open-topped oil storage tanks, based on the above-mentioned wind tunnel experiments and finite element analysis.

1. Introduction

Circular cylindrical shells are widely used for oil storage tanks and other civil engineering structures. The stability of these shells under wind loading is one of the most important technological problems when designing and constructing these structures. Buckling may occur when they are subjected to wind loads in the empty or partially filled state. The buckling is related to the net wind force, or the difference between the pressures on the outside and inside ('external' and 'internal' surfaces) of the cylinder (Resinger and Greiner, 1982; Jerath and Sadid, 1985); these pressures are called 'external' and 'internal' pressures in the present paper both for the closed-topped and open-topped tanks.

For open-topped tanks, in particular, the effect of internal pressure on the buckling behavior may become significant, because the internal pressure is negative and large in magnitude, generating large net wind forces on the cylinder in the windward area (Resinger and Greiner, 1982; Uematsu and Koo, 2008). Even for closed-topped tanks, similar situation may occur when they are under construction and the roofs have not been fixed yet. Indeed, several tanks were collapsed by strong winds (see Holroyd, 1983, for example). When designing these structures, focus should be on the buckling as well as on the wind forces and the resultant stresses involved in the cylinders.

Regarding the stability, or the buckling of cylindrical structures subjected to wind loading, some theoretical and experimental studies were made in the past. For example, Wang and Billington (1974) and Kundurpi et al. (1975) studied the stability of cantilevered cylindrical shells with free edges at the open top, theoretically and/or experimentally. In their theoretical analyses, the pre-buckling state of the shell was determined by Donnell's linear equations. Resinger and Greiner (1982) carried out a wind-tunnel experiment with aluminum shells on the buckling of tank shells and presented an easy-to-handle concept based on an equivalent uniform pressure. The stability of a representative aluminum shell was numerically analyzed by Brendel et al. (1981) using direct integration and finite element method. The effects of pre-buckling nonlinearity and initial imperfection on the buckling behavior were investigated. Jerath and Sadid (1985) theoretically studied the buckling of orthotropic cylindrical shells. Uematsu and Uchiyama (1985) conducted a series of wind tunnel experiments on the deflection and buckling behavior of closed-topped cylindrical shells with aspect ratios (height/diameter ratios) of 1 to 3,

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and gave an empirical formula for evaluating the buckling load. Uchiyama et al. (1987) experimentally investigated the buckling behavior of ring-stiffened circular cylindrical shells in a wind tunnel.

Most of the previous studies, including the above-mentioned ones, were based on the wind tunnel experiments in uniform flows with low turbulence. On the other hand, Holroyd (1983) measured the dynamic wind pressures on an open-topped oil storage tank with an aspect ratio of 0.2 in a turbulent boundary layer. Then, Holroyd (1985) carried out a dynamic response analysis in the frequency domain using the experimental data on wind pressures. He proposed a new criterion for calculating the size of wind girders (stiffening rings for resisting wind forces). However, buckling was not considered in the study. The wind pressure distributions on circular cylinders with relatively small aspect ratios in turbulent boundary layers were investigated by several researchers. For example, Sabransky and Melbourne (1987) measured the wind pressures on circular silos with conical roofs. Macdonald et al. (1988, 1990a, 1990b) measured the mean and fluctuating wind pressures on circular cylinders with flat or conical roofs. However, they did not deal with open-topped tanks.

It is well accepted that the wind pressure distribution on a circular cylinder depends on many factors, such as the Reynolds number *Re*, the approaching turbulence and the aspect ratio of the cylinder. The internal pressure is strongly affected by the roof condition; it is generally negative and larger in magnitude for open-topped tanks than for closed-topped tanks. Such a change in pressure distribution may affect the buckling behavior of cylindrical shells significantly. Therefore, a detailed examination of the effect of pressure distribution on the buckling behavior is necessary for discussing the design wind loads on open-topped tanks.

The present paper discusses the design wind loads on open-topped oil storage tanks, based on wind pressure measurements with rigid models in a turbulent boundary layer as well as on experimental and numerical analyses of the buckling behavior of thin cylindrical shells under wind loadings. Two series of wind tunnel experiments are carried out. In the first series, simultaneous pressure measurements both on the external and internal surfaces of the tank models are made. The pressures on the floating roof at various heights are also measured. However, focus is on the empty condition here and the roof pressures are outside the scope of the present paper. A conditional sampling technique and a POD (Proper Orthogonal Decomposition) analysis are also employed to understand the characteristics of pressure field on the wall in more detail. In the second series of experiments, the buckling behavior of thin cylindrical shells with or without roof is investigated. The buckling tests with thin cylindrical shells are conducted both in a smooth flow and a turbulent boundary layer. The deflection of the shell is measured at the mid-height point on the windward generator. Note that the wind tunnel used for the buckling tests is different from that for the pressure measurements. The distributions of the mean external and internal pressure coefficients are also measured with rigid models in these flows. The results are used as the input data for the finite element analysis of the buckling of cylindrical shells under static wind loading. Based on the results of these wind tunnel experiments and the finite element analysis, a discussion is made of the design wind loads on open-toped oil storage tanks, focusing on the buckling behavior and the dynamic load effects of wind pressures.

It should be mentioned that the present paper is an integrated version of our previous papers (Uematsu and Koo, 2008; Uematsu et al., 2008, 2010; Koo et al., 2010; Yasunaga et al., 2011, 2012a, 2012b).

2. Experimental arrangements and procedures

2.1. Simultaneous pressure measurements

The experiments are 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 approximately 0.15 for the mean velocity profile is generated on the wind tunnel floor, which simulates natural winds over typical open-country exposure. The turbulence intensity I_u and integral scale of turbulence L_x at a height of $z = 125$ mm are approximately 0.16 and 0.6 m, respectively. Three models (Models A to C) with different aspect ratios are used in the experiments. The surface is nominally smooth. The dimensions of the models and the location of pressure taps are shown in Fig. 1. The external diameter D is 250 mm and the wall thickness is 6 mm. The pressure taps of 0.5 mm diameter are installed at a step of 15° on the external surface and at a step of 30° on the internal surface along each circumference.

The pressure taps are connected to pressure transducers in parallel via 80 cm lengths of flexible vinyl tubing of 1 mm inside diameter. The wind pressures at all pressure taps are sampled at a rate of 1 kHz for about 33 s simultaneously. The compensation for the frequency response of the pneumatic tubing system is carried out by using a digital filter to obtain a flat response up to about 500 Hz. The wind velocity U_H at the model height ($z = H$) is approximately 10 m/s; the corresponding Reynolds number *Re* ($= U_H D/\nu$, with ν being the kinematic viscosity of the air) is approximately 1.6×10^5. It is well accepted that the flow around circular cylinders is affected by many factors, e.g. the Reynolds number, surface roughness of the cylinder and turbulence intensity of the flow. Macdonald et al. (1988) investigated the Reynolds number effect on the external pressure distributions on smooth circular cylinders with aspect ratios of $H/D = 0.5$–2.0 in a turbulent boundary layer. They measured the external pressures in the Reynolds number range from 6.6×10^4 to 2.9×10^5 and compared their results on the mean pressure coefficient distributions with those obtained from a full-scale measurements by Cook and

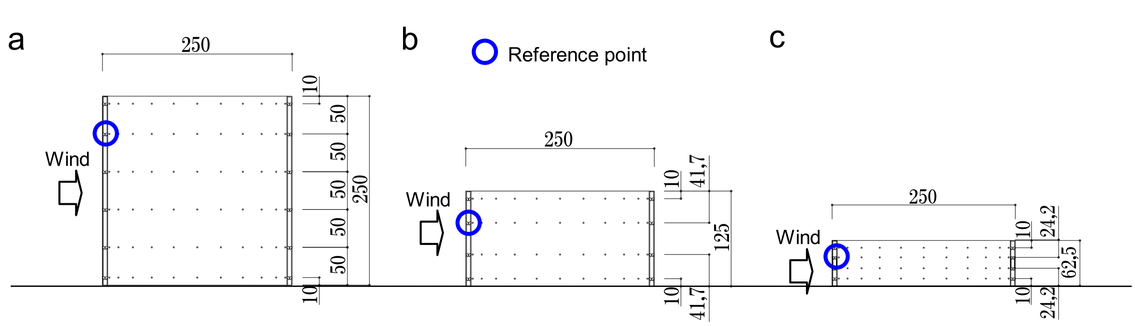

Fig. 1. Dimensions of wind-tunnel models and location of pressure taps on the external surface (unit: mm). (a) Model A ($H/D = 1.0$). (b) Model B ($H/D = 0.5$). (c) Model C ($H/D = 0.25$).