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Wind induced buckling of large circular steel silos with various slenderness

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ABSTRACT

Large steel silos are typical kinds of thin-walled structures that are widely used to store large quantities of granular solids in the industrial and agricultural sectors. In the present analyses, the buckling design of large steel silos subjected to wind pressure is demonstrated in accordance with Eurocode (EN1990, 1991, 1993) and proposed combinational Load Cases WE (wind and empty silo) and WF (wind and full silo). Six steel silos with capacities of 30,000–60,000 m^3 with slenderness from 4.77 to 0.35 and thus representing very slender, slender, intermediate slender, squat and retaining silos are examined as examples. The finite element model is established using the commercial general purpose computer package ANSYS. Five types of buckling analyses are conducted on geometrically perfect and imperfect models with and without consideration of material plasticity. These models are designated as LBA, GNA, GMNA, GNIA, and GMNIA in EN 1993 Part 1–6. The concept of critical wind velocity $v_{\mathrm{b,cr}}$ is put forward and defined for the first time in reference to our wind induced buckling analysis, according to which the silo structure obtains the equivalent buckling strength for Load Case WE and WF. The dominant loading conditions of Load Cases WE and WF can be determined by drawing comparisons between the critical wind velocity and designed wind velocity proposed by meteorological conditions. Nonlinear buckling deformations corresponding to the critical point in Load Case WE are governed by circumferential compression generated in the windward region of shells localized at the top of the silo wall. Nonlinear buckling modes of Load Case WF take the form of well-known elephant-foot deformations found at the base of the shell wall, which are induced by meridional compressive stress. Effects of geometrical and material nonlinearities and weld imperfection on the buckling behaviour of steel silos are very complex and are closely correlated with the slenderness of silo structures.

1. Introduction

Large steel silos are thin-walled structures that are widely used to store large quantities of granular solids in the industrial and agricultural sectors. A silo wall can be supported by two fundamental forms (discrete or ground support) depending on its diameter and capacity. The former type is used for a silo with a small diameter and is constructed using a local bracket or column, creating a limited number of narrow supports around the silo circumference, and the latter is used for large diameter silos (e.g., with diameters of greater than 15 m), which are supported at the base plate with an underpass beneath the flat base [1,2]. With the development of the domestic economy, the number and capacity of steel silos has increased over recent decades. The diameters of certain steel silos are larger than 100 m with capacities of greater than 100,000 m^3. A typical ground-supported circular steel silo with a diameter of roughly 45 m and a height of 36 m (capacity of 57,000 m^3) constructed in Liaoning Province, China is shown in Fig. 1.

A large steel silo is typically constructed of thin steel sheets with a large diameter to thickness ratio and is particularly vulnerable to buckling under wind pressure when the silo is either empty or partially filled. Wind-induced collapse has been found to result in the most catastrophic structural failures among major natural hazards such as hurricanes, earthquakes, flooding, snowfall, etc. A silo's slenderness has a significant influence on the relative magnitude and distribution of solid pressures placed on the internal surface and of wind pressures on the external surface. The wind buckling design of a steel silo structure is dominated by shell wall resistance to buckling failure during operation, which should take two forms of nonuniform pressure into account [1,2,5]: wind pressure placed on the external surface of the silo wall and wall pressure exerted by stored granular solids. It has also been specified [1,2] that solid pressure placed on the vertical wall and circumferential variations in wind pressure must be evaluated according to a silo's slenderness. Design is carried out in accordance with the

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Fig. 1. A typical ground-supported circular steel silo with a capacity of 57,000 m^3.

current European standards EN1990, 1991 and 1993 [1–7] in the following cases.

Wind pressure on the exterior of cylindrical shells such as silos, tanks, bins and chimneys has attracted the interest of many researchers [8] who have tried to measure the distribution and magnitude of wind pressure from site measurements [9], model tests [11], wind tunnel tests [10,12–14], theoretical analyses [15,16], and numerical simulations [17,18]. The buckling of cylindrical shells subjected to wind loads was initially evaluated by theoretical analysis [19–21]. The stability of cantilever shells under wind loads was investigated by Kundurpi et al. [19] based on the principle of energy, and it was found that the critical wind pressure level obtained from maximum external pressure is conservative relative to test results found for uniform external pressure. Results derived from buckling evaluations of thin circular cylindrical shells under wind loads [20] show that prebuckling deflection is extremely sensitive to the wind pressure distribution while buckling pressure is less sensitive to it. The application of a lower bound approach to the buckling analysis of cylindrical shells for tanks subjected to wind loads was reported by Jaca et al. [21] based on a reduced energy model of a shell. The buckling of cylindrical shells subjected to wind loads has also been evaluated through wind tunnel tests [22,23]. For experimental verification, several buckling tests on cylindrical PVC and steel specimens with large radius/thickness ratios subjected to internal underpressure and to a “wind-like” load arrangement have been carried out [22], and recommendations on the development of an economic postbuckling strength design strategy have been put forward. A wind tunnel test on the buckling of oil storage tanks was also carried out by Koo et al. [23] using tinfoil specimens, and corresponding results were compared to theoretical and empirical formulas.

With the rapid development of computers and algorithms, numerical simulations using commercial FE packages have been widely accepted in evaluating the buckling of large steel silos. Wind pressure and the buckling of cylindrical steel tanks with conical and domed roofs are described by Portela and Godoy [13,14], illustrating that buckling occurs in the form of deflections in the cylindrical shell and that the buckling mode is localized in the windward region. A study of anchored stocky and intermediate length cylindrical shells of uniform thickness subjected to wind pressure is presented by Chen et al. [24]. The results show that both linear and nonlinear analyses predict the circumferential compression buckling modes of stocky cylinders. The buckling behaviour of cylindrical shells with stepwise wall thickness subjected to uniform external pressure has also been explored by Chen et al. [25], who make predictions on a broad range of geometries of silos and tanks with both anchored and unanchored base boundaries. Load-bearing capacities of slender wind-loaded cylindrical shells have also been investigated by Schneider and Zahlten [26] with consideration of geometrical and material nonlinearities. The results show that slender shells do not behave as beams under wind loading with stress states, failure loads and failure modes. The buckling of cylindrical steel tanks under wind pressure has been evaluated for conical roofs and open top tanks by Sosa and Godoy [27] to compute a lower bound for critical wind pressures. The authors’ results are compared to a static nonlinear analysis applied to the same models. Buckling results are also derived from other investigations [28,29] on various shell geometries and load conditions. Based on the geometry of a thin-walled cylindrical structure, three different stability failure modes subjected to wind loading are summarized by Pircher [30], who shows that the critical bifurcation mode is heavily dependent on the presence of prebuckling deformations. Postbuckling behaviour is also evaluated by Schmidt et al. [22] via numerical analyses and experimental verification. Wind force coefficients for open-topped oil storage tanks have been evaluated both experimentally and analytically [31], and buckling behaviour of cylindrical shells has been investigated through wind tunnel experiments and finite element analyses. Grouping effects on wind pressure distribution and buckling behaviour have also been explored using experimental and nonlinear finite element methods [32], and it has been found that the distribution of positive wind force coefficients in the windward area significantly affects buckling behaviour.

The effect of imperfections on wind-pressurized cylindrical shells has been evaluated by Greiner and Derler [33] while imperfection sensitivities to the elastic buckling of wind loaded open cylindrical tanks have been reported by Godoy and Flores [34]. The influence of weld-induced axisymmetric imperfections on the buckling of a medium-length silo subjected to wind loading have been explored by Pircher [35], who found that the positioning of a weld along the height of a thin-walled cylinder has a considerable influence on buckling strength under wind loading and that weld-induced residual stress fields slightly reduce buckling resistance. In recent decades, the buckling failures of wind-pressurized steel cylindrical containers, such as silos and tanks, have been frequently reported on. Analytical studies of tanks created for the oil industry that failed during their construction under moderate winds are reported by Jaca and Godoy [36]. Structural effects of major natural hazards (i.e., earthquakes, hurricanes, and floods) on thin-walled metal tanks with large diameters and low aspect ratios have been summarized [37]. Buckling failures of cylindrical shells used as tanks during normal operation under hurricane conditions [38–41] have also been reported on. It has been revealed by a large number of engineering cases that wind loads subjected to cylindrical shell walls predominantly spur the buckling failure of such structures.

The wind induced buckling behaviour of a reference silo with a diameter of 40 m and with an aspect ratio of 0.9 was investigated in an earlier study by Zhao and Cao [42]. The study is however limited in several respects. 1) Only one silo slenderness (diameter of 40 m and height of 36 m (slenderness 0.9)) is evaluated. 2) The critical wind velocity, which is also dependent on silo slenderness, is not discussed in detail. 3) The determination of a dominant load case of wind buckling design is not applied to silos of varying slenderness. 4) Buckling modes can vary considerably with silo slenderness under wind loads. As these problems particularly influence the wind buckling of steel silos, they are the focus of this study. This paper investigates the buckling behaviour of steel silos based on several numerical analyses to further understanding of large circular steel silos subjected to wind pressure when silos are empty or full. The paper is organized as follows. Six large silos ranging from very slender silos to retaining silos examined as examples are described in Section 2. Section 3 then describes load cases relating to wind pressure proposed by Eurocode [1–7] together with wall pressures exerted by bulk solids and wind pressures on external silo surfaces. Section 4 then expatiates upon the perfect and imperfect FE models, the types of buckling analysis and the determination of the buckling strength of silo structures. The concept of critical wind velocity is initially put forward in Section 5, and the relation curve of critical wind velocity to steel silo slenderness is determined. Numerical