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Buckling behaviors and simplified design method for steel silos under locally distributed axial load

Peijun Wang, Xulin Zhu, Mei Liu *, Yang Li

Civil Engineering College of Shandong University, Ji'nan, Shandong Province 250061, China

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ABSTRACT

Buckling behaviors of steel silos subjected to locally distributed axial load (LDAL) were studied by a Finite Element Model (FEM), which was verified by available test and analytical results. Studied parameters included the internal pressure, the Local edge load Center Angle (LCA) and the radius-to-thickness ratio (R/t) of a silo. Buckling modes, distributions of reaction forces along the silo bottom edge and buckling stresses were presented. FEM simulations showed that a compression arch was formed on the silo wall to transfer the LDAL to boundaries; and between the feet of compression arch the reaction was in tension. The span and the height of the compression arch almost did not change with the varying of LCA for silos having the same internal pressure and R/t. However, the height of the compression arch decreased with the increase in internal pressure. A silo under LDAL was more likely failed by elastic buckling when the internal pressure was at low level; and at this circumstance the buckling stress increased with the increase in internal pressure. At high level of internal pressure, buckling failure modes of a silo under LDAL changed from elastic buckling to elastic-plastic buckling; and the buckling stress decreased with the increase in internal pressure. For silos with same internal pressure and R/t, the buckling stress decreased with the increase in LCA. Design equations in EC3-4-1 could overestimate the buckling stress of steel silos under combination of internal pressure and LDAL. Based on parameter study results, a practical design equation was proposed for calculating the buckling stress of a steel silo under combined internal pressure and LDAL. Buckling stresses predicted by the proposed equation agreed well with those obtained by FEM.

1. Introduction

Design loads on a steel silo may include: (1) the internal pressure due to the stored bulk material; (2) the uniform vertical compression caused by load on the silo roof; (3) the frictional drag induced by the stored granular material; (4) the locally distributed axial load (LDAL) from trestle piers fixed on the wall, as shown in Fig. 1, etc. Steel silos shown in Fig. 1 are a widely adopted design. The trestle above silo roof is supported by piers seated on silo wall. Loads caused by trestle piers could be simplified as a locally distributed axial load.

Buckling behaviors and design methods for a steel silo under Uniformly Distributed Axial Load (UDAL) have been fully studied experimentally and numerically [1]. EC3-4-1 [2] provided design equations for the buckling stress of a steel silo under the combination of internal pressure and UDAL. Rotter et al. [3] carried out model tests to investigate the buckling failures directly induced by stored solid. The buckling strength of a silo filled with granular material might be higher than that of an empty one due to the supports from stored granular solid. Winterstetter and Schmidt [4] performed experimental and numerical investigations on cylindrical shells under combined external pressure and shear stress. An analytical method was proposed for calculating the interactive buckling strength. Lin and Teng [5] studied buckling behaviors of an extensively-welded steel cylinder under UDAL. Research results showed that the geometric imperfection had severe effects on the buckling stress. Holst and Rotter [6] investigated the initiation and development of imperfections caused by local differential settlement of base and their effects on the elastic buckling of a thin cylindrical shell under UDAL. They found that the local imperfection of boundary condition in the axial direction could be more deleterious to the buckling strength than that in the direction normal to the wall. Sondej et al. [7] studied buckling behaviors of steel silos with corrugated walls and vertical open-sectional stringers under UDAL through Finite Element Model (FEM). A modification to the design formulae was proposed.

The internal pressure caused by stored granular material could reduce the imperfection sensitivity of steel silo under axial

* Corresponding author.
E-mail address: Meiliusdu@163.com (M. Liu).

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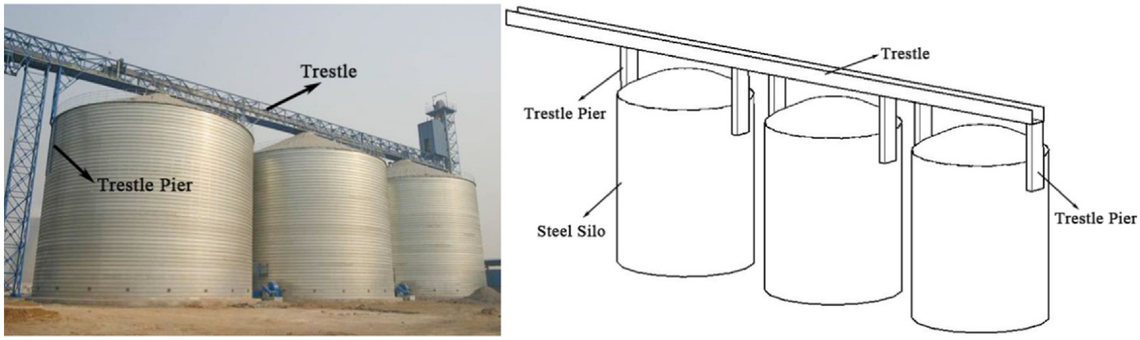

(a)Steel silos with trestles on top (b) Locally distributed axial load from trestle pier

Fig. 1. Steel silo wall under local vertical load caused by trestle piers. (a) Steel silos with trestles on top. (b) Locally distributed axial load from trestle pier.

compression to buckling failure. Hutchinson [8], Rotter [9] and Ansourian [10] had proved the beneficial effects of bulk material on the buckling behavior of a steel silo. Greiner et al. [11] studied buckling behaviors of unstiffened cylinders on local supports under combination of axial load and internal pressure. Study results showed that the buckling stress in general could been enhanced by the internal pressure. Khelil et al. [12] studied buckling behavior of cylinder shells subjected to combination of internal pressures and wall frictional through experiment and numerical simulation. An analytical method was developed to determine the stress distribution in the silo wall. Wang and Zheng [13] proposed a design equation for the buckling stress of steel silo under combination of internal pressure and UDAL, as results of FEM parameter studies.

Buckling behaviors and the design method for a steel silo under LDAL would be different to those under UDAL. Song et al. [14] presented the load carrying capacities and the imperfection sensitivity of the silo under the bilateral symmetric LDALs. Research results released that the geometric imperfection greatly affected the buckling stress of a steel silo. Wang and Cao [15] proposed design recommendations for a thin-walled cylinder with circumferential weld imperfection with the LCA less than 10°. Basic variables of design equations were the imperfection amplitude and the radius-to-thickness ratio (R/t). Cai et al. [16] carried out a detailed study on the buckling mode and buckling stress of a steel silo with large LCA. Hotala et al. [17] studied the local buckling of a silo supported by columns by test and FEM. Buckling stress of the stiffened shell supported discretely was always much smaller than that supported uniformly. The local buckling that was caused by axial force from supporting columns was discussed by Pasternak [18] and studied through FEM by Jansseune et al. [19]. Distributions of the axial stresses in the silo wall along circumference direction were presented. Sonat et al. [20] performed a numerical study on the elastic–plastic buckling of imperfect silos resting on discretely supported ring beams. A design method was proposed to determine the degree of non-uniformity in the axial stresses.

The trestle pier brings LDAL to the silo wall, whose effects on buckling behaviors of a steel silo have not been fully studied yet. In this paper, the buckling behavior and buckling stress of a steel silo under combination of internal pressure and LDAL were studied by the FEM using the software ABAQUS. Studied parameters included the internal pressure, the LCA and R/t. Buckling modes, distributions of reaction force along the silo bottom edge and buckling stress caused by the LDAL were presented. Buckling stresses of steel silos under the combination of internal pressure and LDAL obtained from FEM were compared with those under combination of internal pressure and UDAL calculated by code equations [2]. Based on parameter study results, a design equation was proposed for calculating the buckling stress of a steel silo under the combination of internal pressure and LDAL.

2. Finite Element Model and verification

2.1. Finite element model

The Finite Element Model (FEM) was conducted using the software ABAQUS. Buckling behaviors of a steel silo are mainly determined by R/t, instead of individual radius, R, or wall thickness, t. In this study, the variation of R/t was obtained through changing R. The wall thickness, t, was kept constant as 10 mm. The distribution of internal pressure P_{he} in steel silo was non-uniform, as shown in Fig. 2(a), and the thickness of the silo wall was changed along the silo height correspondingly. If a short height of the silo was studied, the distribution of internal pressure could be treated as uniform, as shown in Fig. 2(b). For simplify the analysis, a uniform distribution of internal pressure was assumed.

To reduce the unwanted influences of boundary conditions on the silo buckling behavior, the silo height should be greater than 2R [13]. Here, the silo height, H, took 3R. The silo was subjected to the combination of a uniform internal pressure and a UDAL or a LDAL with center angle of α, as shown in Fig. 3. The shell element S4R, a four nodes reduced integration finite strain shell element, was used to mesh the silo wall.

The three translation freedoms of the silo bottom edge were fixed. For the silo top edge, only the radical and circumferential translation freedoms were fixed. The internal pressure was applied on the silo wall through the Pressure Load option in ABAQUS.

The material property of steel was assumed to be perfect elastic-plastic. The Young's modulus $E = 205$ GPa and the Poisson's ratio $\upsilon = 0.3$. The steel was assumed to be Q235 with the yield stress $f_y = 215$ MPa.

2.2. Analysis procedures

Three types of analysis were adopted here, which were:

1) the Linear eigenvalue Buckling Analysis of a perfect steel silo (LBA) under UDAL to obtain the buckling mode which was used as the geometric imperfection;
2) the Linear eigenvalue Buckling Analysis of an Imperfect steel silo (LBIA) with internal pressure subjected to LDAL to obtain the elastic buckling stress of a silo under the combination of internal pressure and LDAL; and
3) the Geometric and Material Nonlinear Analysis of an Imperfect steel silo (GMNIA) with internal pressure subjected to LDAL to obtain the elastic-plastic buckling stress of a silo under the combination of internal pressure and LDAL. Instead of applying the LDAL directly and then using the Riks method in ABAQUS to capture the load-displacement curve, a local axial displacement was applied on the silo top edge and the axial reaction force was the corresponding LDAL. The maximum value on the load-displacement curve was defined