Journal of Constructional Steel Research 139 (2017) 411–423

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Structural performance of double-wall steel insulation silo with multiple bolted joints

Gan Tang [a], Lingfeng Yin [b,*], Zhanjie Li [c], Chaohui Pan [a], Haibin Lai [b]

[a] Department of Civil Engineering, Nanjing University of Aeronautics and Astronautics, YuDao Street 29, Nanjing 210016, China
[b] School of Civil Engineering, Southeast University, SiPaiLou 2, Nanjing 210096, China
[c] Department of Engineering, SUNY Polytechnic Institute, Utica, NY 13502, USA

A R T I C L E I N F O

Article history:
Received 10 September 2016
Received in revised form 17 May 2017
Accepted 19 September 2017
Available online xxxx

Keywords:
Double-wall silo
Multiple bolted joints
Bearing patterns
Internal and external plate
Geometric imperfection

A B S T R A C T

The purpose of this study is to study the structural behaviors of a double-wall insulated steel silo under a storing loading with concentric discharge. Current silo structures are predominantly single-wall thin-wall silos, which have a lack of thermal insulation capability. This innovative double-wall silo consists of internal and external walls with multiple bolt connections and ring beams, which can not only provide effective insulation but also enhance the stability and bearing capacity of the structure. However, the structural performance and bearing mechanism of the double-wall silo are not well understood. In this study, a 1000-t double-wall steel silo designed according to specifications was computationally studied via a set of analyses using ANSYS, including linear bifurcation, linear elastic, geometric nonlinear, geometrically and materially nonlinear, and geometrically and materially nonlinear with imperfections. These analyses revealed a cooperative bearing mechanism of the silo walls. In particular, 2/3 of the vertical friction is borne by the external wall, while the majority of the horizontal pressure is borne by the internal wall. The results also highlighted the stress distribution of the silo walls under a storing load. The results of a nonlinear analysis indicated that the failure mode was an “elephant's foot” deformation if the material plasticity was included. Compared with that without material plasticity, the studied silo exhibited plasticity-dominant behavior. The double-wall silo has advantages over the single-wall silo such as better insulation and structural performance.

1. Introduction

Owing to their structural efficiency and ease of construction, steel silos are widely used for grain storage. Currently, steel silos are largely manufactured as single-layer thin-wall silos without an insulating layer. Their structural behaviors have been extensively studied. The structural behaviors of the silo structure are subjected to, predominantly, a combination of horizontal pressure and vertical friction (i.e., axial compression in the wall) within a complex dynamic discharging process. Many in-depth studies on the dynamic discharging process, such as those of Artoni et al. [1] and Zhong et al. [2], led to no definitive conclusion regarding the forming mechanism of the lateral pressure in this dynamic process. For simplified computation, the formula proposed by Janssen [3] for the horizontal pressure and the vertical friction of silos has been adopted in the design standards of many countries (China [4], Australia [5], Europe [6], ISO [7], United States [8], etc.). Many researchers have proposed modifications and improvements of Janssen's formula for a better representation of this dynamic process. Steel silos with thin walls infamously suffer stability issues. Pincher and Bridge [9], Teng and Chan [10], and Sadowski and Rotter [11] studied the impact of initial imperfections on the structural behavior. Investigations of the collapse behavior and the eccentric load effect of a steel silo were reported by Laier et al. [12], Dogangun et al. [13], and Sadowski and Rotter [14]. Moreover, advanced analyses, such as hypoplasticity theory with the intergranular strain approach were used to examine the interaction between the granular material and the silo structure [15].

Single-layer thin-wall steel silos often have a structural configuration comprising a corrugated steel plate and vertical reinforcing ribs. The corrugated steel sheet mainly bears the lateral pressure from the stored grains, and the vertical load is entirely borne by the reinforcing ribs. The reinforcing rib is a flexural-compression member under both symmetry and eccentric discharging. The corrugated sheet and reinforcing ribs are frequently connected with bolts for an economical design. Regarding the behaviors of single-layer thin-wall silos, the potential large displacement at the top can cause structural damage (or even collapse) to the silo, as reported by Kuczyńska et al. [16] and Zhao and Teng [17,18]. Moreover, for single-layer thin-wall silos without insulation, studies showed that the stored grains were significantly affected by the external environment with only a single layer of thin steel. The condensation of moisture was observed in the silo, and a high and imbalanced distribution of the grain temperature frequently appeared in

* Corresponding author.
E-mail address: eking@seu.edu.cn (L. Yin).

https://doi.org/10.1016/j.jcsr.2017.09.020

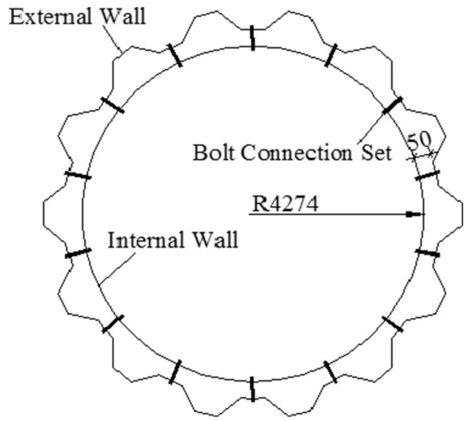

Fig. 1. Cross-section of the double-wall insulation silo.

the summer. Thus, the poor thermal insulation property of the steel silo may deteriorate the stored grains and ultimately increase the cost of grain storage.

To provide insulation and better structural performance to the conventional (single-layer) steel silos—in particular, to improve the structural integrity between the steel plate and reinforcing ribs—an innovative double-wall steel insulation silo with multiple bolted joints was proposed (see Fig. 2). The proposed silo was patented in China [19]. A scaled structure of the proposed silo system was experimentally investigated by the authors [20]. The experiment and associated numerical simulations elucidated the bonding mechanism and revealed significant improvements in the structural performance [21]. In this study, the structural performance of the proposed double-wall insulation silo was numerically investigated with respect to its bearing mechanism and collapse pattern by utilizing a full-scale numerical model under a storing load with symmetric discharge. The paper is organized as follows. First, the structural configuration and modeling details are discussed. Then, several analyses on the full-scale numerical model, i.e., bifurcation, linear elastic, geometric nonlinear, and geometrically material nonlinear, performed to gain a comprehensive view of the structural behavior under the specified load are presented. Thus, the bearing mechanism and potential collapse patterns are investigated in detail. Finally, a brief comparison with the single-layer steel silo is presented.

2. Double-wall insulation silo

The study was performed on a 1000-t double-wall steel insulation silo with an internal diameter of 8.548 m, a height of 20.540 m, and a spacing of 50 mm between the internal and external sheets. The double-wall steel insulation silo comprised an external silo wall made of a corrugated steel sheet with a wave height of 75 mm and an internal wall made of a thin-wall circular steel sheet. Insulated roof sandwich panels were used to form an enclosure on the top of the silo. The cross-section of the proposed silo is illustrated in Fig. 1. A full sketch of the silo is presented in Fig. 2, with architectural details. Information about the wall corrugation of the silo is shown in Fig. 3.

Instead of using a monolithic sheet, the proposed silo employed 17 sheets along the direction of its height for both the external and

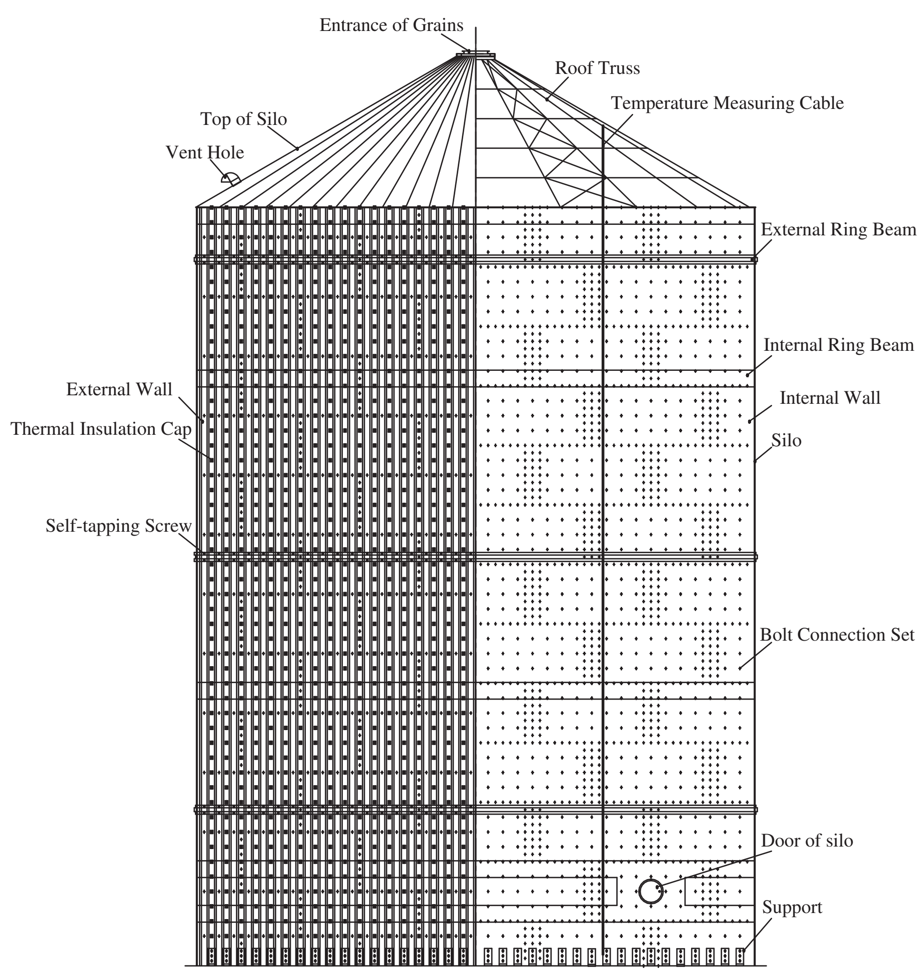

Fig. 2. Double-wall steel insulation silo with multiple bolted joints.