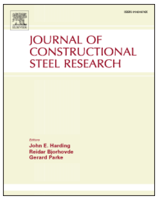
Journal of Constructional Steel Research 129 (2017) 227–239

Contents lists available at ScienceDirect

Journal of Constructional Steel Research



Structural system and buckling design of cellular steel silos

Qing-shuai Cao [a,b], Yang Zhao [a,*]

[a] Space Structures Research Center, Zhejiang University, Hangzhou 310058, China
[b] Department of Civil Engineering, Zhejiang University City College, Hangzhou 310015, China

ARTICLE INFO

Article history:
Received 17 May 2016
Received in revised form 8 October 2016
Accepted 4 November 2016
Available online xxxx

Keywords:
Steel silo
Buckling
Cellular
Hexagon
Geometric nonlinearity
Material nonlinearity

ABSTRACT

Large steel silos are widely used to store huge quantities of granular solids in industry and agriculture. In the present analysis, a novel type of silo structure, designated the cellular silo, is proposed and discussed. The performance advantage of the cellular silo is the clustered construction of individual hexagon silos, which can be formed by different numbers and arrangements of cell silos. The structural system is firstly determined for the cell silo by comparison between the plate model and 3D-stiffened plate models, and it is shown that the 3D-stiffened plate assembly composed of shell elements and beam elements is feasible for the cell silo, which is quite distinct from the shell structure fit for circular silos. The horizontal solid pressure, which is beneficial to circular silos, is unfavourable to the buckling of cell silos, and the buckling design is governed mainly by the horizontal pressure rather than the vertical frictional pressure. The buckling behaviour of group silos is investigated by considering load cases defined by the number of working cell silos and their relative position in the group. The common features of group silos during buckling are summarized, and it is referential for structural design of a cellular silo. An illustrative example of a cellular silo is presented at the end to demonstrate the design procedure, and it is concluded that the buckling design of the cellular silo is governed by the full loading condition and can be completed by optimization of the cell silos and their combinations.

1. Introduction

The inspiration of many structural designs originates from explicit knowledge about the nature of human lives. By researching biological shapes, some novel concepts can be created for the design and construction of structures. The cellular silo is a successful engineering construction used as a novel type of structure that has drawn inspiration from the honeycomb. The honeycomb of bees is a delicate and applicable structure composed of a large number of hexagonal cells with the same dimensions, as shown in Fig. 1. The cells in honeycombs are hexagonal columns surrounded by other cells, and the cells are isolated only by a very thin wax wall. The structure of the honeycomb in nature is representative of the most effective structure that creates the most space with the minimum material consumption. The skills and powers of the honeybee are so attractive that the human beings constantly conduct studies on honeycombs in attempts to simulate honeycombs in modern applications. The cellular structure has been successfully used in a number of notable areas, such as the space shuttle, artificial satellites, and spacecraft. Based on the concept of bionics, a new type of silo structure, designated the cellular silo, is proposed for storing huge quantities of granular solids in industry and agriculture.

In the present analysis, the cellular silo is designed with hexagonal walls of stepped thickness, an outlet beneath each hexagon, and a dome roof on the top and above affiliated buildings. The performance advantage of a cellular silo is the clustered construction of hexagon cells, which could be formed by different numbers and arrangements of hexagon silos, designated as G2, G3, G4, …,G16, etc., as shown in Fig. 2. The arrangement of a cellular silo could optimize land use compared with circular group silos, as the silo wall is shared and there is no gap between neighbouring hexagons. The walls of a cellular silo are planar, so flexure of the steel plate, which is essential to circular silos in the process of construction, is no longer required. The designed thickness of the hexagonal silo wall is much thinner than that of a circular silo with equivalent diameter. In such a case, the connection of the wall plate by welds is more reliable, and the construction of a steel silo is simplified. The cellular silo is usually designed by the configuration of several group silos with a specified spacing between groups, and the number of hexagons in each group (shown in Fig. 2) can be defined by the principle that cell silos are convenient for the construction of group silos and for combinations among group silos. For clarity of terminology, an individual silo in the cellular structure is referred to as a cell silo in the following discussions.

For thin-walled circular silos, the load case of eccentric discharge has been widely recognized as the most dangerous loading condition and has been the cause of many catastrophic buckling failures [8–11]. Nonetheless, the conditions are quite different for a cellular silo when it is eccentrically discharged. The cell silos are designed to be isolated by common walls with the assorted outlet underneath, which means that each cell silo is independent during the period of service. The diameter

---

[*] Corresponding author.
E-mail address: ceyzhao@zju.edu.cn (Y. Zhao).

http://dx.doi.org/10.1016/j.jcsr.2016.11.003
0143-974X/© 2016 Elsevier Ltd. All rights reserved.

Fig. 1. A cellular structure in nature.

of a cell silo is usually within the range of 5.0–10.0 m for ease of construction, and the sole outlet is always located at the centre of the bottom, so that the individual cell silo is concentrically discharged during the service period. For cell silos that are not positioned at the geometric centre of a cellular silo, discharging occurs with a certain amount of eccentricity relative to the cellular silo. The impact of discharging a cell silo on the cellular silo is related to the number and position of the working cell silos. However, the impact of an individual cell silo is limited to the neighbouring cell silos, and the effects on the interval cell silos are minimal. As a result, the large eccentricity, which has the strongest unfavourable effect on circular silos, is insignificant in the structural design of a cellular silo.

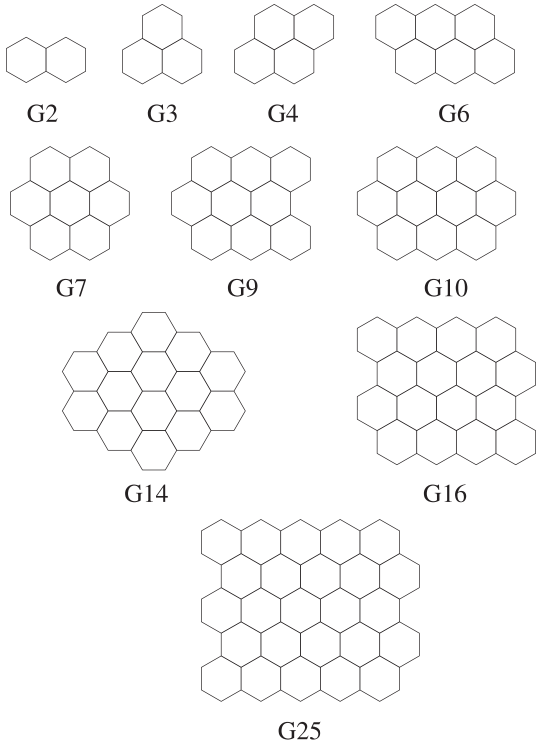


Fig. 2. Plane arrangements of various numbers of hexagon group silos.

The significant difference of cellular silos with respect to circular silos results from the planar configuration, where the wall of a cellular silo is planar without curvature. As a result, the design of the silo wall for a cellular silo is distinct from that of circular silos, where the structural behaviour of the silo wall exhibits the plate-like features rather than shell features. The structural behaviour of plate has received considerable attentions in recent decades. Linear elastic buckling was investigated [12] for plates with various load and supporting conditions, and the elastic buckling load of uniaxially loaded rectangular perforated plates [13] was determined for simply supported edges in the out-of-plane direction when subjected to uniaxial end compression. Linear buckling analysis of unstiffened plates under interacting patch loading and bending moment was investigated [14] by focusing on estimation of the elastic critical load due to patch load. The linear buckling of simply supported thin plates subjected to patch compression was also evaluated [15], and the buckling coefficient was determined for different load cases applied to a range of plates with various edge ratios. The buckling and post-buckling behaviour of steel plates subjected to variations in their initial conditions was also investigated [16], including the variation in aspect ratio, boundary conditions, initial out-of-plane imperfection and material elastic and plastic properties. The results of a parametric study to quantify the effect of lateral pressure on the collapse of square and rectangular steel plates under a predominantly compressive load were reported [17], and the load-shortening behaviour of square and rectangular plates under the combined effect of longitudinal compression and lateral pressure was determined using general-purpose nonlinear finite element code for different breadth to thickness ratios. The design of longitudinally stiffened plates under direct stress was demonstrated according to Eurocode [18]. The strengthening effects of stiffeners on regular and arbitrarily stiffened plates were discussed in terms of the ultimate strength limit obtained through full nonlinear transient analysis [19].

This paper investigates the structural system and buckling behaviour of cellular silos through numerical analyses. The aim is to expound the fundamental concept of the cellular steel silo and the design procedure when subjected to discharging solid pressure. The layout is organized as follows: The possible structure models for hexagon cell silos are proposed in Section 2. The load distribution on the walls of a cell silo and the design conditions are presented in Section 3. Section 4 then expounds upon the analysis procedure for cellular silos, including the finite element model of the cell silo and the primary parameters for buckling design and the determination of the wall pressure distribution by the Eurocode [1–7]. Four numerical models for the structural system of a cell silo are compared in detail in Section 5, and a feasible structural system for cellular silos is determined, which is a new type of structure called a 3D-stiffened plate assembly. The buckling behaviour of the 3D-stiffened plate assembly is investigated by nonlinear full-course load-displacement curves. Buckling analysis is performed in Section 6 for group silos in consideration of various discharging load cases defined by the number of working cell silos and their relative position in the group. The common features of group silos, which is referential for buckling design of cellular silos, are also summarized. An illustrative example of a cellular silo is presented in Section 7 to demonstrate the design procedure, and some valuable conclusions that are expected to improve the understanding of the buckling behaviour of cellular silos under discharge for multiple load cases are obtained in Section 8.

2. Geometry and proposed structural system for the cell silo

A hexagon cell silo with side length l_c of 9.3 m and wall height h_c of 23.55 m is chosen as an example silo for the following discussion, as shown in Fig. 3. The nominal diameter d_c can be determined by EN 1991-4 [1]: $d_c = \sqrt{3}\,l_c = 16.108$ m, and the aspect ratio of the cell silo can be obtained by: $h_c/d_c = 1.462$, which is in the range of intermediate