Engineering Structures 33 (2011) 1187–1194

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Buckling of very slender metal silos under eccentric discharge

Adam J. Sadowski *, J. Michael Rotter

University of Edinburgh, Scotland, UK

ARTICLE INFO

Article history:
Received 13 August 2010
Received in revised form
9 December 2010
Accepted 29 December 2010
Available online 3 February 2011

Keywords:
Thin shell structures
Solids flow
Structural stability
Nonlinear computer analysis
Shell buckling
Imperfection sensitivity
Geometrically nonlinear

ABSTRACT

Metal silos used to store granular solids often take the form of a cylindrical shell with an aspect ratio in the range $2 < H/D < 6$. It has long been recognised that the most serious load case for all silos is probably the condition of eccentric discharge of its stored solid, but in circular metal silos this is especially true. More failures have occurred under this condition than any other. This high failure rate is chiefly due to the complexity of the pressures exerted by an eccentrically discharging granular material, and the difficulty in understanding the pattern of stresses that develops in a shell wall under such unsymmetrical pressure regimes. The nonsymmetric behaviour of a shell structure under unsymmetrical pressures is not at all well described in the voluminous shell structures literature, and only a few studies have explored the mechanics leading to high local stresses which in turn lead to buckling failure under eccentric discharge.

This study follows an earlier initial exploration by Sadowski and Rotter (2010) [2], in which buckling in a moderately slender perfect silo was explored. Here, the work is taken further to explore a very slender structure, and to investigate the imperfection sensitivity of this failure mode. The pressures caused by eccentric discharge are characterised using the new rules of the European Standard EN 1991-4 (2006) [1] that define the actions in silos and tanks. Using this new improved description of unsymmetrical eccentric discharge pressures, it is now possible to perform relatively realistic calculations relating to this common but complicated shell buckling condition. The shell buckling calculations described here employ a pressure distribution formulated with the assumption of a parallel-sided flow channel and are undertaken using geometrically and materially nonlinear analyses in accordance with the European Standard EN 1993-1-6 (2007) [25] on the strength and stability of shells. The paper explores the structural behaviour of a slender silo under eccentric discharge, leading to buckling and including the critical effects of changes of geometry and imperfection sensitivity.

1. Introduction

It has long been recognised that the pressures on the walls of silos for the storage of granular solids change considerably from the state of filling and storing to the state of solids discharge. The latter case dominates silo design. But of all the potential patterns of pressure during discharge, the condition in which a channel of flowing solid develops against one part of the wall of a circular silo is by far the most demanding. This condition, termed eccentric discharge, has led to many serious and catastrophic failures and is most damaging of all in slender metal silos (a slender silo has an aspect ratio greater than 2 according to EN 1991-4 [1]). The failure mode in such slender thin-walled silos is buckling due to local axial compressive stresses, which are induced by unsymmetrical normal pressures against the wall.

In an earlier study [2], the phenomenon of buckling in a moderately slender perfect silo was explored. The basic mechanics were described, but it was not possible to determine how significant the effects of slenderness and imperfection sensitivity might be. Since these two aspects are particularly important in metal silos, they are the subject of this study. Further features of the problem, notably the question of what should be taken as failure, are also discussed. The significance of the category "very slender" is illustrated by the patterns of solids flow in silos shown in Fig. 1, which is taken from EN 1991-4 [1].

When the silo is eccentrically discharged (see Figs. 2 and 3), a very unsymmetrical pattern of normal pressures on the silo wall can arise, which leads to greatly increased local axial compressions that dramatically exacerbate the problem of buckling [5,6]. A moderately realistic representation of the resulting pressure pattern is, for the first time, codified in the relatively recent European Standard EN 1991-4 [1]. The reader is invited to consult [7,8,4,9] for background material on flow patterns and loadings in silos to illustrate the scope and load cases found in the EN 1991-4 [1] standard.

In this paper it is shown that failure under eccentric discharge is by buckling in the elastic range of material behaviour under local axial compressive membrane stresses induced by this highly unsymmetrical flow regime. This explanation is supported by

* Corresponding author. Tel.: +44 131 5579727.
E-mail address: a.j.sadowski@ed.ac.uk (A.J. Sadowski).

0141-0296/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.engstruct.2010.12.040