International Journal of Solids and Structures 96 (2016) 92–109

Contents lists available at ScienceDirect

International Journal of Solids and Structures

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

Imperfection sensitivity of locally supported cylindrical silos subjected to uniform axial compression

Arne Jansseune [a,*], Wouter De Corte [a,b], Jan Belis [b]

[a] Department of Structural Engineering, Faculty of Engineering and Architecture, Ghent University, Valentin Vaerwyckweg 1, 9000 Ghent, Belgium
[b] Department of Structural Engineering LMO, Faculty of Engineering and Architecture, Ghent University, Technologiepark 904, 9052 Zwijnaarde-Ghent, Belgium

ARTICLE INFO

Article history:
Received 15 May 2015
Revised 14 April 2016
Available online 15 June 2016

Keywords:
Cylinder
Locally supported
Yielding
Buckling
Axial compression
Imperfection sensitivity

ABSTRACT

For the prediction of the real failure load of shell structures, such as locally supported cylindrical steel silos under axial compression, it is convenient to take into account imperfections. It is assumed that such silos are very sensitive to a wide range of (even small) geometric imperfections, and that they lower the failure load significantly. Furthermore, these imperfections caused by the fabrication or the manufacturing process, are the dominant factor in the discrepancy between the theoretical/numerical predictions based on a perfect geometry and the experimental results of an imperfect geometry. In other words, it is important to make a well-considered choice for an imperfection when predicting the real failure load. However, the imperfection sensitivity depends, among other things, on the shape of the shell, the stiffening configuration, the boundary and loading conditions, etc. Before proceeding to the calculation of interaction curves and the development of new design rules for imperfect barrels, it is essential to perform an extensive study to examine the influence of imperfections to the failure behaviour and to choose a sufficiently detrimental imperfection shape.

In this study, different imperfection forms are numerically investigated: the linear bifurcation mode, the non-linear buckling mode, several post-buckling deformed shapes of the perfect shell, and a weld depression type A and B. Additional aspects, such as the orientation, the amplitude of the equivalent imperfection, and the position of the influence of the weld depression are also investigated. The present study takes into account the European normative documents and the guidelines of the recommendations of the ECCS.

1. Introduction

For many branches of industries and during different stages of the manufacturing process, steel silos play an important role in the storage requirements of bulk solids. The steel barrel frequently has a cylindrical shape and is placed in elevated position by a limited number of supporting columns (Doerich, 2007; Jansseune et al., 2013a, 2013b, 2015a, 2015b). As a consequence of this way of support, the total load exerted on the structure (mainly vertical) has to be transferred to a relatively small proportion of the total circumference at the bottom of the barrel, resulting in locally high axial stress concentrations and failure due to excessive yielding and/or local instability.

In this paper, the failure behaviour of locally supported shells will be examined for two supporting/stiffening arrangements. The first type are silos supported by engaged columns, without the presence of ring stiffeners (Jansseune et al., 2013a, 2013b). These columns have a rectangular or a square cross-section, and are attached to the silo wall by welding. This relative simple type of support is used for smaller silo structures (Rotter, 2001). In the second configuration, the supporting columns are extended to the bottom of the silo wall and are concentrically placed beneath the centre of the silo wall (Vanlaere, 2006). Above each supporting column, a longitudinal U-shaped stiffener is placed, which is attached (i.e. welded) along a specific distance to the silo wall (Jansseune et al., 2013a, 2013b, 2015a, 2015b). These U-shaped stiffeners absorb a large part of the vertical loads, depending on the relative stiffnesses of the stiffeners and the silo wall. In this case, two extra ring stiffeners are provided at the lower edge of the cylindrical barrel, and at the top of the stringer stiffeners. This stiffening configuration is used for intermediate to large silo structures (Rotter, 2001). Despite the difference in geometry between both configurations, both have in common that the ground reaction force is gradually introduced into the silo wall by shear, spreading the load better in circumferential direction, increasing the failure load.

* Corresponding author.
E-mail address: Arne.Jansseune@UGent.be (A. Jansseune).

http://dx.doi.org/10.1016/j.ijsolstr.2016.06.019

Whereas the authors focused on the influence (Jansseune et al., 2013a, 2013b, 2015a, 2015b) and the optimisation (Jansseune et al., 2015a, 2015b) of the stiffening configuration (i.e. the engaged columns and the U-shaped longitudinal stiffeners) to the failure behaviour for perfect silos, attention is now turning to the impact of geometrical imperfections. Since all real structures are imperfect and since the failure behaviour of axially compressed steel silos is extremely susceptible to imperfections, it is of exceptional importance to take into account imperfections when predicting the real failure load. Even very small imperfections can cause a significant reduction in the load carrying capacity. These imperfections, which are caused by the fabrication or the manufacturing process, are the dominant factor of the discrepancy between the theoretical/numerical predictions based on a perfect geometry and the experimental results of an imperfect geometry. In other words, it is highly desirable to consider such (geometric) imperfections to be able to predict the real failure load. Before being able to deduce buckling or interaction parameters of imperfect silos, this much-needed research is an important step to explore the failure behaviour of locally supported imperfect silo structures subjected to axial compression, in combination with U-shaped longitudinal stiffeners or engaged columns.

2. Imperfection shapes

2.1. Approaches for the choice of an imperfection shape

Since locally supported thin-walled steel silos subjected to axial compression are highly sensitive to a wide range of imperfections, and the imperfection sensitivity depends on the amplitude of the chosen imperfection, it is very difficult to single out one imperfection shape and amplitude, which is sufficiently disadvantageous for one geometry (as designer during the design process) or for all geometries (as researcher). The latter is necessary if further progress has to be made in the development of design rules. However, it is not possible to select an imperfection shape from previous research, since the imperfection sensitivity depends on the shape of the shell, the corresponding stiffening configuration, and the boundary and loading conditions. Furthermore, several studies considered multiple defects simultaneously in the structure, such as different localised imperfections (Limam et al., 2011), localised and distributed imperfections (Jamal et al., 2003), or patterned welds consisting of circumferential and/or meridional welds (Hubner et al., 2006; Pircher and Bridge, 2001a, 2001b), possibly causing (strong) interaction between the defects. Because of the above mentioned reasons, it is an enormous challenge as a designer/researcher to choose one (or a combination of) specific imperfection(s). In general, there are three main philosophies for choosing an imperfection, as described by Schmidt and Rotter: (1) the most realistic imperfection shape, (2) the worst imperfection shape, and (3) an equivalent imperfection shape (Schmidt, 2000; Rotter, 2004; ECCS, 2008).

2.1.2. Realistic imperfections

The first conceptual approach is to model geometric imperfections **as "realistic" as possible** based on measurements of similar silo structures (full-scale shells (Coleman et al., 1992; Ding et al., 1991; Teng et al., 2005) or laboratory shells (Mathon and Limam, 2006; Jansseune, 2015)), while residual stresses and material imperfections are frequently neglected, because of the difficulties to quantify them (ECCS, 2008). Arbocz was probably the first who used such measurements of imperfections in aerospace shells (Arbocz, 1974; Arbocz and Sechler, 1974; Arbocz and Babcock Jr, 1976). Currently, such measurements are only to a limited extent available on large steel silos, because of the cost and the difficulties of its execution and implementation (e.g. define the best-fit surface of the silo wall, Fourier decomposition, etc.). Moreover, it is not obvious to derive a (preferably simple) equivalent geometric imperfection shape in a feasible and repeatable manner for typical civil engineering structures (Arbocz, 1983).

2.1.3. Worst possible imperfections

Searching to **the very "worst possible" geometrical shape** (within a specific range of tolerance) is the second approach, and is intended to provide a safe lower bound for design. This method has been used from the beginning that imperfections were introduced, and can in principle be applied for different shell problems. To find the most severe shape, parametric studies have been done for specific problems (Greiner and Derler, 1995; Błachut and Jaiswal, 1999). Others used mathematical investigations to deal with this topic (Jamal et al., 2003; Koiter, 1963; Deml and Wunderlich, 1997). However, nowadays, these attempts are not widely spread in the design stage of shell structures. Furthermore, such methods are difficult to apply due to several inevitable shortcomings: real structures generally do not necessarily have the "worst" mode as geometric imperfection, and the "worst" mode frequently is far from realistic (Rotter, 2004). In other words, it is doubtful that this method provides imperfections which are close enough to real silo structures, and consequently simulate the real imperfection sensitivity and the failure behaviour in practice. Furthermore, underpredictions of the real buckling strength are not economical. In conclusion, this method is less appropriate to determine the buckling strength by numerical simulations with the most severe geometrical imperfection shape.

2.1.4. Simple equivalent imperfections

The third and last approach is the use of **a relatively simple "equivalent" geometric imperfection**. Such a shape might perhaps not be 100% realistic nor is it the most severe possible shape, its main purpose is to sufficiently influence the behaviour of the silo (in an adverse way) to reduce the buckling load. Likely candidates to be used as equivalent shape are shapes which have a certain degree of geometric similarity to either failure patterns (such as buckling or post-buckling modes) or the fabrication-caused shape deviations (e.g. an axisymmetric weld depression) (ECCS, 2008). These imperfections are modelled as initial shape deviations perpendicular to the middle surface of the perfect silo wall.

Since it is the purpose to develop design rules according to the Eurocode (EN 1993-4-1, 2007a, EN 1993-1-6, 2007b), the last approach, namely the use of equivalent geometric imperfections, was adopted in the current investigation as prescribed by the requirements of the European normative documents (EN 1993-4-1, 2007a, EN 1993-4-6, 2007b). The reason for this choice is simply that, at this moment, the use of "equivalent" imperfections is by far the most suitable approach to predict realistic failure loads by a numerical analysis (ECCS, 2008). Furthermore, the present study takes into account the guidelines and the commentary of the recommendations of the ECCS (ECCS, 2008).

2.2. Equivalent imperfection shapes

2.2.1. Shape

In previous work, different imperfection shapes have been suggested for the use as equivalent geometric imperfection: a linear or non-linear bifurcation buckling mode of the perfect shell (LBM or NBM) (Greiner and Derler, 1995; Koiter, 1963, 1945; Brendel and Ramm, 1980; Yamaki, 1984; Combescure, 1986; Speicher and Saal, 1991; Wunderlich and Albertin, 2000; Guggenberger et al., 2000; Song et al., 2004; Song, 2002), a post-buckling deformed shape (PDS) (Guggenberger et al., 2000; Song et al., 2004; Song, 2002; Guggenberger, 1998; Schneider et al., 2001; Esslinger and Geier, 1972), or a combination of (bifurcation) buckling modes