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Optimal stiffening configuration for locally supported cylindrical silos: Engaged columns

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ABSTRACT

Cylindrical steel silos are often supported by discrete supports or columns to be able to provide a hopper and to facilitate emptying operations beneath the cylindrical barrel. The simplest mean of support for a light silo is by the use of engaged columns, without the use of unnecessarily expensive ring stiffeners. Such engaged columns gradually introduce the support load into the silo wall by shear, spreading the stresses in circumferential direction. In general, the highest axial compressive stress concentrations can be found in the shell wall in the vicinity of the top of the engaged column, resulting in failure due to excessive yielding and/or local instability.
The study aims to identify the optimal combination of dimensions of an engaged column (i.e. the height, the widths in circumferential and radial direction and the thickness) to obtain a failure load as high as possible with as little material in the column as possible. An important condition is the requirement that the columns must withstand a higher load than the silo wall itself. In other words, failure should occur in the vicinity of the terminations of the columns (and not in the column itself). All results and conclusions are based on numerical finite element analyses.

1. Introduction

Steel silos are widely found in many branches of industries for the temporary storage of bulk solids during different stages of the manufacturing process. For practical reasons, it is often necessary to place such a silo in elevated position to be able to provide a hopper below the barrel and to conveniently discharge the content of the silo by gravity flow [1–4]. For this, a possible solution is to support the barrel by a limited number of equidistant columns around the circumference. However, this way of supporting is detrimental for the structural behaviour of the silo because high reaction forces are locally introduced at the bottom of the cylindrical wall. Since the silo is for the most part exposed to vertical load, and high axial compressive stress concentrations occur in the silo wall just above the supports; premature failure is caused due to plastic yielding for thick-walled silos, elastic buckling for thin-walled silos, or a combination of the aforementioned phenomena for silos with an intermediate thickness.

In this paper, the supporting columns are eccentrically positioned on the exterior side of the silo wall, and these columns are engaged into the silo wall over a specific distance [5,6]. This supporting arrangement is an economical and simple way to improve the failure behaviour and is used for smaller silo structures [7]. The columns usually have a rectangular cross-section and are welded to the silo wall along the edges. Along the attached height, the supporting reaction force is transferred gradually into the silo wall by shear, spreading the load better in circumferential direction, reducing the peak stresses in the silo wall near and above the column.

This study addresses the optimisation of the dimensions of the engaged column based on the results of an extensive parametric study, as for a wide range of column geometries, numerical simulations (geometrical and material non-linear shell analyses or GMNA analyses) were done with the finite element package ABAQUS [8].

Based on the results and the findings of this paper, the author has two main purposes [9]. Firstly, it is intended to determine the best combination of dimensions of the engaged columns as the target of a good engaged column is to achieve a maximum failure load for a minimum amount of steel. Moreover, it should be absolutely avoided that the columns fail prematurely at a lower load level than the silo wall can resist. The influence of all geometrical parameters will be described and related to the failure behaviour of such locally supported silos. The second purpose is related to the structural design of metal silos according to the European standards and will be discussed more in detail in the following paragraphs.

The European standard on the structural design of steel silos divides silos into classes according to the mass of solid stored: 100, 200 (with eccentric discharge/filling, or local patch loading) or 1000 (in elevated position) or 5000 (ground supported) tonnes [10]. While small silos (CC1: 10–100 tonnes) can be designed using simple calculations, greater design effort is demanded for moderate large silos (CC2: 100–1000

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tonnes) and very large silos (CC3: >1000 tonnes). For example, a validated numerical shell analysis (using finite element software) may or should be used for the structural design of CC2 or CC3 silos, respectively [10,11].

One of the design approaches for the buckling limit state is the MNA/LBA approach, which is a combination of two simple numerical shell calculations (a material non-linear analysis or MNA and a linear elastic bifurcation analysis or LBA) and hand calculations. In short, the latter includes the determination of the relative slenderness λ, the choice of buckling or interaction parameters, the determination of the dimensionless strength parameters χ, and finally the characteristic and design value of the resistance R.

At this moment, there are, however, no buckling parameters available for locally supported stiffened steel silos with a clear *non-uniform axial compressive stress* distribution in the circumferential direction. Therefore, the designer has to estimate the buckling parameters (preferably conservative) by comparing the problem with similar buckling cases, taking into account as much as possible relevant information such as geometry, boundary conditions, loading pattern, dominant stress pattern, influence of imperfection sensitivity and geometric non-linearity, expected (post-)buckling behaviour, etc. [12]. However, when these parameters cannot be estimated with sufficient confidence, then the Eurocode suggests to use the most advanced and complex GMNIA method or to use the "default" values of the buckling parameters. It is important to mention that these parameters were derived on the basis of calibration against a wide range of experimental results of *uniformly compressed cylinders*.

For this reason, the second main target of the findings in this paper is to define a scope of geometries for which new capacity curves will be developed according to the generalised design concept methodology [13]. Afterwards, these curves will be used to deduce new interaction or buckling parameters [9,14] which hopefully can be introduced in the Eurocode 3 in addition to the current conservative buckling parameters for uniform meridional compression [11]. In this way, it is hoped that the MNA/LBA methodology becomes more accessible for the design of the buckling limit state of locally supported stiffened cylindrical steel silos [11,12].

2. Geometry

2.1. Silo geometry

The dimensions of the cylindrical barrel are given in Table 1. The only dimension of the whole structure which has an absolute value is the cylinder radius R. The other dimensions are expressed as dimensionless quantities, and are relative to the cylinder radius R. In this paper, two values of the radius-to-thickness ratio are used to investigate the failure behaviour of both thick-walled silos (i.e. $R/t = 200$) and thin-walled silos (i.e. $R/t = 1000$). Furthermore, the cylindrical barrel was chosen sufficiently high to exclude the effect of the cylinder height to the failure behaviour [15]. For this reason, the silo's height is always taken equal to 8 times the cylinder radius R.

2.2. Geometry of the supports

In this study, a constant number of 4 supporting columns is considered. These supporting columns are distributed over the whole circumference with equally spaced intervals, are engaged into the silo wall, and are attached to the external face of the silo wall (see Fig. 1(a)). Because of this support eccentricity, moments are introduced into the silo wall, which are disadvantageous for such an axially compressed silo.

The dimensions of the supporting columns are further discussed in Section 2.3 — geometry of the engaged columns, because the supports have the same cross-section as the engaged columns ($d_{sup} = d_{stif}$; $w_{sup} = w_{stif}$; $t_{sup} = t_{stif}$).

Table 1
Geometrical parameters of the cylinder.

Parameter	Value(s)	Dimension
R	1.0	m
R/t	200; 1000	–
h/R	8.0	–

2.3. Geometry of the engaged columns

Theoretically, the supported proportion of the circumference can vary from zero (i.e. $\mu_{sup} = 0$) to a condition where the entire circumference is supported (i.e. $\mu_{sup} = 1$). In this study, the supported proportion of the circumference μ_{sup} is close to zero. For the thick-walled silos (i.e. $R/t = 200$), the ratio of the circumferential width to the cylinder radius d_{stif}/R ranges between 0.10 and 0.30, corresponding a supported proportion of the circumference μ_{sup} of respectively 0.064 and 0.191. For the thin-walled silos (i.e. $R/t = 1000$), d_{stif}/R is varied between 0.05 ($\mu_{sup} = 0.032$) and 0.20 ($\mu_{sup} = 0.127$).

In this study, the ratio of the radial width to the circumferential width w_{stif}/d_{stif} is varied between 0.25 and 4.0. This investigated range corresponds with a large set of different shapes of the cross-section, as illustrated in Fig. 2. From this figure, it could be wrongly deduced that the circumferential width d_{stif} remains constant, but as mentioned before, the width d_{stif} will also vary.

In addition, the range of the column thickness is determined by two restrictive conditions. Firstly, because of the necessity to weld the engaged column to the silo wall, a minimum thickness (i.e. 1× the silo thickness) and a maximum thickness (i.e. 5 times the silo thickness) is imposed (Eq. (1) in Table 2). The second condition that should be met is that the column should not be too thick or too thin compared to its circumferential width d_{stif} (Eq. (2) in Table 2). This restriction is presented in Fig. 3 and is based on local compression induced by local buckling considerations [16]. Class 4 cross-sections are those cross-sections in which local buckling will occur before the attainment of yield stress in one or more parts of the cross-section [16]. Such "too-thin" cross-sections are not considered here.

For such engaged columns, the total column height is divided into an "unattached" height h_{stif}^{inf} and an "attached" height h_{stif}^{sup} (see Fig. 1(a)). The "unattached" height h_{stif}^{inf}, which is the height between the bottom of the cylindrical barrel and the clamped lower edge of the engaged column, is equal to a fixed value of 4.0 times the cylinder radius R. This value corresponds with a 75° angle hopper and sufficient clearance under the hopper, to easily empty the contents of the silo. As will be discussed later in detail, this situation (i.e. a high engaged column) is the most disadvantageous situation with regard to the failure behaviour of the silo [5]. The "attached" height h_{stif}^{sup} represents the height over which the engaged column is attached to the silo wall. This height is varied between 0.5 and 2.0 times the cylinder radius R.

All geometrical parameters of the engaged columns, including the imposed restrictions, are given in Table 2.

2.4. Geometry of the ring stiffeners

For practical considerations (i.e. to reduce the costs of material and construction), no ring stiffeners are added to the relative small/light silo structure, as is usually the case when engaged columns are used [7].

3. Numerical model

All findings are based on numerical analyses performed with the commercial finite element package ABAQUS [8]. Shell elements (S8R5) [8] are used, both for the cylindrical barrel and the engaged columns. These elements are rectangular 8-node doubly curved shell elements and represent the midsurface of each component. Furthermore,