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Investigations of local/global buckling of cylindrical metal silos with corrugated sheets and open-sectional column profiles

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ABSTRACT

The paper deals with buckling of cylindrical metal silos with corrugated sheets and columns. Attention was paid to local buckling of cold-formed open-sectional thin-walled columns in metal cylindrical silos with corrugated sheets. The effect of the column profile dimensions, silo height, silo diameter, corrugated wall thickness, column number/column distance, corrugation height and bulk solid's type was comprehensively investigated. Three-dimensional linear bifurcation analyses were performed for silos using the finite element method and compared with analytical formulae of Eurocode 3. Based on calculation outcomes some recommendations for silo dimensioning were elaborated.

1. Introduction

Silos are engineering structures widely used in industries and farms to store, feed and process bulk solids that is essential to agricultural, mining, mineral processing, chemical, shipping and other industries [1,2]. They are mainly built of concrete or metal (steel and aluminium). Metal silos can be built of thin-walled isotropic plain rolled sheets (which can be welded, riveted or screwed around the silo perimeter) or of thin-walled corrugated curved sheets strengthened by cold-formed open-sectional thin-walled columns distributed uniformly around the silo circumference and connected with screws. Those latter are frequently used in the engineering practice due to an economical steel consumption and a small silo weight. In these silos, it is assumed that horizontally corrugated wall sheets carry circumferential tensile forces caused by the horizontal wall pressure and columns carry vertical compressive forces due to the vertical wall friction traction exerted from bulk solids. A common mechanical failure form in all metal silos is a stability loss caused by the compressive wall friction force due to the interaction between the silo fill and silo wall, particularly during eccentric filling and discharge [3,4] and dynamic mass flow [5–8]. In contrast to silos composed of isotropic plain rolled sheets, there exist a few research works on global buckling of cylindrical metal bins composed of horizontally corrugated sheets and strengthened by vertical columns. The first theoretical solutions regarding the buckling strength of stiffened shells were elaborated in the papers [9–13] based on the smeared stiffener approach. The first experiments on stiffened shells were described by Weller and Singer [14,15], Singer [12,16] and Card and Jones [17]. In experiments, the influence of geometric imperfections, load distribution and stringer locations on the buckling strength was investigated. In contrast to the non-stiffened shells, the stiffened ones indicated more repeatable results. Other theoretical approached to stiffened shells were given in [18–20]. The formulae in Eurocode 3 (EC3) [21] regarding silos with corrugated walls are based on the DMV theory for pure non-stiffened shells [22–24]. The more accurate solution for pure orthotropic shells was presented by Sanders [25], however due to its complexity, the DMV theory was used in EC3 [21]. The FE buckling analyses on cylindrical stringer stiffened shells were carried out in [26]. The comprehensive FE buckling 3D analysis results for silo shells composed of corrugated walls and open-sectional column profiles were described in [27–31]. The FE analyses of silos composed of corrugated walls replaced by flat walls with the substitute orthotropic stiffness and columns replaced by beam elements were performed by Sondej et al. [32,33] and Iwicki et al. [34]. Rotter et al. [35] presented a bending theory for orthotropic shells under axisymmetric pressure distributions. In FE simulations of silo shells composed of corrugated walls by Kuczyńska et al. [36], a strengthening effect of the presence of the bulk solid in silos on the buckling strength was taken into account. Experiments in a full-scale cylindrical silo with corrugated sheets and open-sectional column profiles (containing wheat) were conducted by Wójcik et al. [37].

The treatment of global buckling within the framework of EC3 [21] provides two different procedures to calculate the buckling strength of vertical columns around the silo circumference depending upon the column distance, that significantly differ from each other. In the case of a silo with sparsely distributed columns, the EC approach is very conservative since it does not take into account a real 3D behaviour of silo

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shells containing a silo fill [32–34,38]. In order to capture more realistically buckling process in silos, it is advantageous to apply the finite element method (FEM) which enables to carry out among others linear bifurcation analyses (LBA), non-linear static analyses or non-linear dynamic analyses [39]. LBA is the simplest analysis, used to estimate critical loads and buckling forms. In turn, non-linear analyses (based on the equilibrium path between the load and displacement) determine the ultimate load by taking into account the effect of the material and geometric characteristics.

The paper deals with global/local buckling of cylindrical metal bin composed of horizontally corrugated sheets strengthened by vertical open-sectional thin-walled columns. The aim of three-dimensional (3D) numerical analyses using FEM was to determine in numbers the effect of the column profile dimensions, silo dimensions (height and diameter), column number/column spacing, corrugated wall dimensions (thickness and height) on local buckling with respect to global buckling. The silos with the diameter of $D = 6–16$ m were subjected to numerical analyses. To our knowledge, such comprehensive studies on local buckling have not been performed yet. In the first step, linear bifurcation/buckling studies were carried out with a perfect silo shell only (as in [40]). The axisymmetric vertical load imposed by bulk solids according to EC1 [41] was taken into account. The positive effect of wall pressure was not considered. The studies were limited to one open-sectional column profile shape (type 'C'). They were mainly carried out with barley. The numerical results for silos were directly compared with EC3 [21]. Our outcomes are important for the safety and optimization of silos in order to avoid local buckling of open-sectional column profiles. Note that a strengthening effect of the bulk solid stiffness against the wall deformation to the silo inside is stronger during global buckling [42].

2. Problem

Depending upon the geometry expressed by the corrugated wall thickness, wall corrugation, column number, profile shape and thickness and structure diameter, silos may lose their stability in a global way or local way. If closed column profiles are used (e.g. rectangular or circular cross-sections), local stability loss does not apparently take place. However, such profiles cannot be used in silos due to the lack of the screw connection possibility of columns with wall sheets. In case of single open-sectional column profiles (Fig. 1), three types of buckling forms may be observed according to EC3 [40]: local, distortional and global buckling. Local instabilities occur when some wall parts of profile cross-sections have characteristic single bulges (Fig. 1a). The distortional instability is characterized by deformation of profile side walls which alternately bend to the inside and outside (Fig. 1b). Note that these rules are not directly related to open-sectional columns in silos as they are stiffened by corrugated sheets. The silo column height does not have a great effect on the buckling form as in the case of single

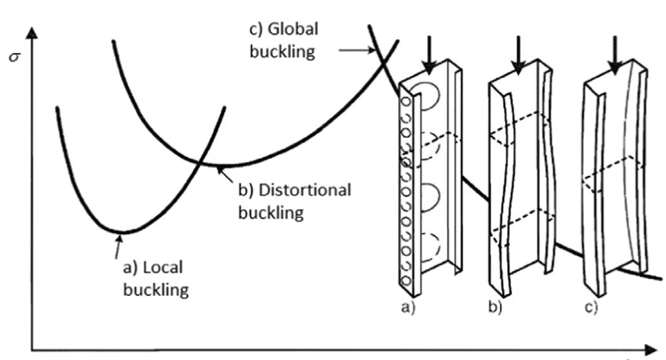

Fig. 1. Single column buckling stress σ versus half-wave length k and buckling form under vertical load: a) local buckling, b) distortional buckling and, c) global buckling [40].

columns. The global column buckling shape is close to the classical Euler one (Fig. 1c). The global silo buckling strength is strictly connected to the number of circumferential buckling waves. The EC3 [21] approach allows for investigating the global silo buckling strength with two sets of formulas depending on the column spacing d_s. The critical value determining the stability calculation approach is calculated as:

$$d_{s,max} = k_{dx} \times \left(\frac{r^2 \times D_y}{C_y}\right)^{0.25}, \tag{1}$$

where: D_y - the flexural rigidity per unit width of the thinnest sheet parallel to the corrugation, C_y - the stretching stiffness per unit width of the thinnest sheet parallel to the corrugation, r – the cylinder radius and $k_{dx} = 7.4$ (coefficient). When the column spacing is smaller or equal to $d_{s,max}$, the silo stability is determined as for an orthotropic shell (Eq. (2)).

$$n_{x,Rcr} = \frac{1}{j^2 \times \omega^2} \times \left(A_1 + \frac{A_2}{A_3}\right), \tag{2}$$

where: $n_{x,Rcr}$ - the critical buckling stress resultant, j - the circumferential wave number and ω, A_1, A_2 and A_3 - the coefficients including the flexural and stretching stiffness in orthogonal directions of the equivalent orthotropic cylinder. Eq. (2) [21] is based on the DMV theory [22–24]. The following assumptions were met to lay down Eq. (2):

- the cylindrical shell is loaded by vertical forces prescribed at both ends only (horizontal pressure is not considered),
- the resulting smeared stiffness is uniformly distributed,
- the equivalent shell mid-surface is taken as the central axis of corrugation,
- the cylindrical shell has hinge supports at ends,
- the buckling mode radial displacements are described by trigonometric functions.

If the horizontal distance between the columns $d_s > d_{s,max}$, the buckling resistance should be determined for individual columns using the second approach:

- by ignoring the supporting action of wall sheets in resisting buckling displacements normal to the wall or
- by allowing for the stiffness of wall sheets in resisting buckling displacements normal to the wall that seems to be more realistic. The design buckling resistance of a single vertical column in this method is given by

$$N_{b,Rd} = 2 \times \sqrt{EI_y \times K}, \tag{3}$$

where $N_{b,Rd}$ – the critical buckling resistance, EI_y – the column flexural rigidity for the out of the plane wall bending and K - the flexural stiffness of sheets between columns.

The following assumptions were taken into account:

- the 2D behaviour of the column (beam) is considered only,
- the number of buckling half-waves along the circumference is equal to the half of the columns number (if the number of column is a multiple of 4),
- the column is loaded by vertical forces prescribed at both ends,
- the horizontal pressure is not considered,
- the column is supported at one side by elastic springs simulating the presence of corrugated sheets,
- the column has hinges at ends.

Eq. (3) may be analytically derived from the equilibrium equation for a vertical column supported by an elastic foundation [27,28]. Eqs. (2) and (3) are conservative (in particular Eq. (3)) since do not take into account real 3D behaviour of a silo shell. According to EC3 [21] the