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Buckling of cylindrical metal shells on discretely supported ring beams

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ABSTRACT

Silos in the form of cylindrical metal shells are usually supported on evenly spaced columns in applications where an access space is needed for the discharge of contained solids. In large silos a ring beam is used to distribute the column forces into the shell. The presence of discrete supports results in a circumferential non-uniformity of axial stresses in the shell. This non-uniformity leads to high local stresses that must be considered in assessing the possibility of shell buckling. Design standards provide recommendations for the buckling of shells under uniform axial compression, but are largely silent concerning stress peaks that may vary in width. Designers must resort either to onerous finite element analyses that include both geometric and material nonlinearities with imperfections (GMNIA) or trust to their own judgment. This paper presents a parametric study to develop resistance or capacity curves which can be used directly in design without the need for complicated analysis. The proposed design method uses only hand calculations apart from a simple linear finite element analysis to determine the degree of non-uniformity in the axial stresses.

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1. Introduction

Cylindrical metal silos are often supported on a few column supports to permit the discharge of the stored granular solids by gravity into transportation systems. A typical arrangement is shown in Fig. 1. There are stringent limitations on the number of column supports that can be used because many columns cause a serious restriction for the transportation system, which is commonly trucks, trains or conveyors. Unfortunately a small number of columns leads to a significant non-uniformity in the axial membrane stresses, so the good structural solution of a large number of columns is usually ruled out by functional requirements.

Different support arrangements may be chosen (Fig. 1) depending on the size of the structure [1]. For small silos, terminating columns with rings (Fig. 1a), engaged columns (Fig. 1b) or bracket supports (Fig. 1e) may be suitable. In medium and large silos it is necessary to use either columns extending to the eaves (Fig. 1c) or a heavy ring beam (Fig. 1d) or double rings (Fig. 1f). Classical design treatments [2–5] assume that the axial membrane stress in the cylindrical shell above a ring beam is circumferentially uniform, so that the criterion for buckling under axial compression corresponds to the uniform compression situation [6]. However, previous work by the authors has shown that extremely stiff rings are required to achieve relatively uniform support [7–9].

The provisions of design standards such as the European Standard on Strength and Stability of Shell Structures EN 1993-1-6 [10] can be used to assess the stability of a cylindrical shell under uniform compression, but the design of a discretely supported cylindrical shell presents several additional challenges. Studies of discretely supported cylinders by earlier authors [11–19] have shown that the behavior is very complex. Regardless of the arrangement, the presence of discrete supports results in axial compressive membrane stresses that are very peaked above the supports, with changing patterns and maximum stresses that decay nonlinearly with height above the supports. Each support arrangement results in a unique variation of axial membrane stresses in both the axial and circumferential directions. Published research to date on buckling of cylinders above local supports has focused on the simple cylindrical shell on discrete supports [16–20], which is a rare situation in practice. Conditions of localized elevated axial compression have also been studied [21–23], but these cannot be easily applied to the conditions above a ring beam. No specific explorations ever appear to have been conducted into cylindrical shell buckling in the practically important situation of a shell resting on a discretely supported ring beam.

Topkaya and Rotter [7,8] studied the effect of the stiffness of a supporting ring beam for a cylindrical shell silo and devised a criterion to assess the degree of non-uniformity in axial stresses for a given ring beam geometry. This study showed that only a very stiff ring beam can produce a relatively uniform axial stress distribution in most applications. It was found that non-uniformity of the axial stresses was almost always unavoidable in practice, so this effect must be considered in the stability assessment of the

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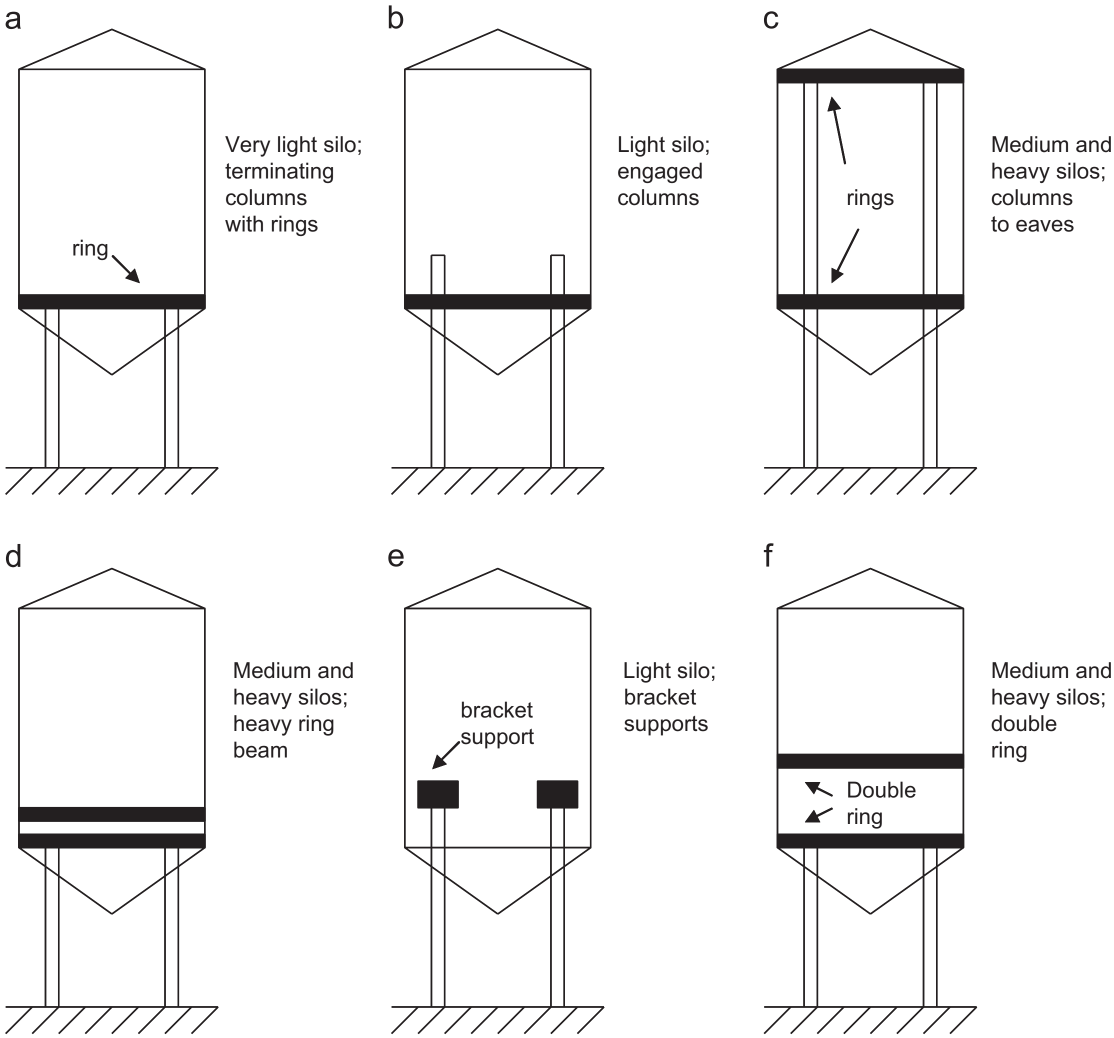

Fig. 1. Alternative support arrangements for discretely supported silos (adapted from Rotter [1]).

shell. Design standards either use the simplest traditional model outlined above, or make no provision for a cylindrical shell resting on discrete supports.

The European Standard on Strength and Stability of Shell Structures EN 1993-1-6 [10] defines the requirements for the use of numerical assessment analyses of various complexity [24,25]. These are linear elastic analysis (LA), linear elastic bifurcation analysis (LBA), materially nonlinear analysis (MNA), geometrically nonlinear elastic analysis (GNA), geometrically and materially nonlinear analysis (GMNA), geometrically nonlinear elastic analysis with explicit imperfections included (GNIA), and geometrically and materially nonlinear analysis with explicit imperfections included (GMNIA). Naturally GMNIA is the most reliable method to determine the buckling strength of any shell, but GMNIA is extremely onerous and is not suitable for routine design practice.

The LBA–MNA methodology [25] can be applied to many problems to simplify the design process. This method is requires only the reference elastic buckling and plastic resistances to be obtained using LBA and MNA, with the interaction between the two and the effects of geometric imperfections accounted for using a capacity or resistance curve that is defined using a few key parameters. The design process can be further simplified if it is possible to devise algebraic expressions to describe the reference resistances from the LBA and MNA analyses.

The primary focus of this paper is to develop the critical information to permit the LBA–MNA methodology to be applied with confidence to shells resting on discretely supported ring beams. The problem was systematically studied through a parametric study. Finite element analyses of different complexity were conducted on a wide range of geometries to obtain the buckling resistances. The details of the finite element models are described here, followed by the selection of design cases based on the parameters that influence the response. The results of an imperfection sensitivity study are described and the predictions of LA, LBA, GNA, GNIA, MNA and GMNIA analyses are presented. Finally, capacity curves are developed that can be used in design calculations in connection with the established LBA and MNA reference resistances.

2. Finite element modeling details

Finite element analyses were conducted using the commercially available program ANSYS [26]. For a cylindrical shell resting on n equally spaced discrete supports, there are $2n$ planes of symmetry. To reduce the computational effort, a segment covering and angle of π/n was modeled as shown in Fig. 2. An I-section ring beam was used as detailed below. The cylindrical shell and the ring beam were both modeled using eight-node shell elements (shell93). In all analyses the ring beam was assumed to remain elastic to prevent any premature failure mode interfering with the shell buckling study. By contrast, the cylindrical shell was modeled

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