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# Effects of patch loads on structural behavior of circular flat-bottomed steel silos

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**Abstract**

The present paper investigates the structural behavior of circular steel silos subject to patch loads. For reference purposes, first the patch loads are assumed to be in two squares that are in generally accordance to silo loading codes [DIN 1055. Design loads for buildings. DIN 1055 Part 6, Deutsches Institute fur Normung, Berlin; May 1987; Bases for design of structures—loads due to bulk materials. ISO11697; 1995]. The investigations reveal that the patch loads have a great effect on the stress states in the silo from the linear elastic analysis (LA). Geometrical non-linearity and primary pressures have beneficial effect. Fourier decompositions of the two square-shaped patch loads show that the effect of the shape of patch loads depends not only on the harmonic index, but also on particular stress component. For a pressure with a lower harmonic index (e.g. cos $\theta$, cos $2\theta$), only limited effect was observed for all stress components. A pressure with medium-sized harmonic index (cos $4\theta$, cos $6\theta$) has a great effect on meridional compressive stress, while for higher harmonic index; the effect was significant for von Mises equivalent stress. Buckling analyses with geometrical non-linearity and material non-linearity taken into account show that the effect of patch loads could be covered by a certain percentage increase of the vertical frictions, if the patch load approach were adequate to represent the non-uniformity of wall pressures in circular flat-bottomed steel silos.



*Keywords:* Steel silos; Patch loads; Shells; Finite element analysis; Buckling; Non-uniform pressure

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## 1. Introduction

Circular steel silos have been widely used in civil engineering to store various bulk solids. Design of silos has to take two kinds of non-uniform pressures into considerations: (a) wind loads and (b) wall loads induced by bulk solids. The former is closely connected with empty silos, while the latter with fully filled silos. Structural behavior of empty silos subject to wind loads have been investigated in detail by many researchers [3–9].

On the other hand, despite buckling failures having been re-produced in early laboratory tests [10–12] and frequently reported of late [13–14], only limited researches have been carried out on the effects of non-uniform pressures caused by bulk solids [15–20]. The investigation of the structural behavior of steel silos is inextricably linked with the description of wall pressures. In the literature, there are dozens of models for the distribution of horizontal wall pressures in silos [21], but no accurate and commonly accepted one is available in this time. Due to the complexity of horizontal pressure distributions, investigations of non-uniform pressures caused by stored bulk solids on structural behavior of steel silos are based on simplified horizontal wall pressure models. Silo loading codes suggest that horizontal pressures consist of two components: axisymmetric (primary) pressures and locally distributed pressures. Therefore, the non-uniformity of the pressures is expressed through adding or subtracting locally distributed pressures to the primary pressures. The locally distributed pressures have different terminology in silo loading codes, for example, partial pressures in the German DIN standard [1], patch loads in International standard [2] and in Part 4 of Eurocode 1 [22], reduced and increased pressures in the Australian standard [23]. In the present paper, the patch loads is adopted for the locally distributed pressures.

Rotter [15] investigated the pressure distributions and the structural behavior of silos under eccentric discharge. Linear elastic analyses indicated that non-uniform pressures produced highly non-uniform axial compressive stresses, which in turn worked as catalyst to silo wall buckling. The suggested method in [15] to assess the buckling strength of silos under non-uniform axial compressive forces was later employed for a reference silo ($D = 12$ m and $H = 3D$) [17]. The assessment illustrated that buckling failure might occur well above the wall of a silo. Gillie and Rotter [20] carried out parametric studies to investigate stress distributions in silos subject to patch loads. The parameters included (a) the distribution within; (b) the position of; and (c) the distribution area of the patch loads. The investigations [15–17,20] revealed that that the stress distributions in silos subjected to non-uniform pressures were very complex. Significant Mises stress and compressive membrane stresses arose in the wall of silos, which meant that both elastic buckling and plastic collapse were possible. However, these researches were based on the linear elastic theory, the effect of material and geometrical non-linearity was not included. Guggenberger's research [19] involved both material and geometrical non-linearity. The distribution of the horizontal pressures was generally in line with silo loading codes [1,2]. The research [19] leads to the conclusions that (a) geometrical non-linearity has a significant beneficial effect and (b) material