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Silos and tanks in research and practice: state of the art and current challenges

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Abstract

Silos and tanks are probably the commonest form of large engineering shell structure in service, but their placement on industrial sites and out of the public eye often leads them to be neglected by researchers and the public alike. The high rate of structural failure in these structures is a strong indication of the extensive range of issues that must be understood by the designer and the complexity of their behavior. This paper outlines some of the most critical aspects of the loading, structural behavior and failure modes of silos and tanks, and points in many places towards the need for additional research to permit better regulation of these very varied and complex structures.

Keywords: Silo, tank, steel shell, concrete shell, loading, earthquake design, failure modes, buckling, plasticity, multi-segment shell.

1. Introduction

Silos and tanks are widely used in a great many different industries for storing a huge range of different solids and liquids. The sizes of engineered silos may vary from capacities less that ten tonnes to the largest containing as much as 100,000 tonnes. Tanks similarly vary greatly in size from a few metres in diameter to over 100 metres. The size of the structure has a strong bearing on the number of different considerations that must be taken into account in structural design: small silos and tanks usually do not present significant structural problems, but large silos and tanks lead to very varied situations where many different aspects need careful attention.

Tanks can take on a huge range of structural forms, and not infrequently have distinctive architectural features to take advantage of their visibility (Figure 1). By contrast, although the designs used for silos vary very much (Figure 2), they are chiefly confined to industrial locations and rarely exploited for publicity purposes. In some industries (e.g. on-farm grain storage), there is a competitive industry producing standard silo products which function extremely well and cost-effectively provided the conditions remain those anticipated in their design. In other industries (e.g. cement and mineral ore storage or port facilities) very large silos are used and every silo must be individually designed for the special conditions. It should be noted that each silo is normally designed to contain a very limited range of solids, and that the use of a silo designed for one kind of solid to store different solids can easily cause damage. Bulk solids vary very much in their properties, and a silo that is perfectly adequate to store one material may be very dangerous for another.

a) Large oil tanks, Czech Republic   b) Elevated water tank, USA   c) Concrete elevated water tank, France

Figure 1: Different geometries and sizes of tank

This paper refers extensively to the provisions of the recently developed European standards for actions on silos and tanks (EN 1991-4 [5]), for structural design of metal shells (EN 1993-1-6 [6]), silos (EN 1993-4-1 [7]) and tanks (EN 1993-4-2 [8]), for which the author was a chief contributor and editor. Further useful information relating to the structural design of silos may be found in Rotter [16] and extensive information and background material relating to the buckling of metal shells is given in the recently published 5th Edition of ECCS Recommendations on the Stability of Steel Shells [21].

2. Loading on silos and tanks

2.1. Storage loads in silos and tanks

For tanks, the storage loads are generally simple and are often governed by the need for a water test. By contrast, storage and discharge loads in silos are complex and depend on a huge range of conditions, from the stored material and its propensity to develop cohesion, to the method of deposition, the potential for segregation, the pattern of flow of the solids, and the properties of the silo walls, as well as the geometry of the container.

2.2. Discharge loads in silos

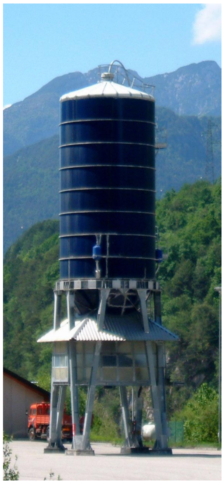
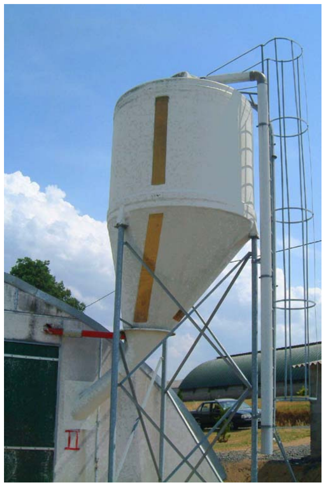
Silo design is dominated by discharge loading conditions, which remain significantly unpredictable even in the early 21st century. The most comprehensive design standard for these loads is the new Eurocode EN 1991-4 [5] which defines different classes of silo by size, aspect ratio, wall roughness and construction material, as well as requiring a range of properties to be considered for the stored solids and requiring several different loading conditions to be examined in design calculations. Overall, this is probably the most complex part of silo design, and failures in silos are very commonly attributed to errors due to misinterpretation of the stored solid rather than errors in structural assessment.



a) 10,000 tonne steel grain storages, Australia

b) Corrugated steel storage, Germany

c) Rectangular concrete silo battery, Austria

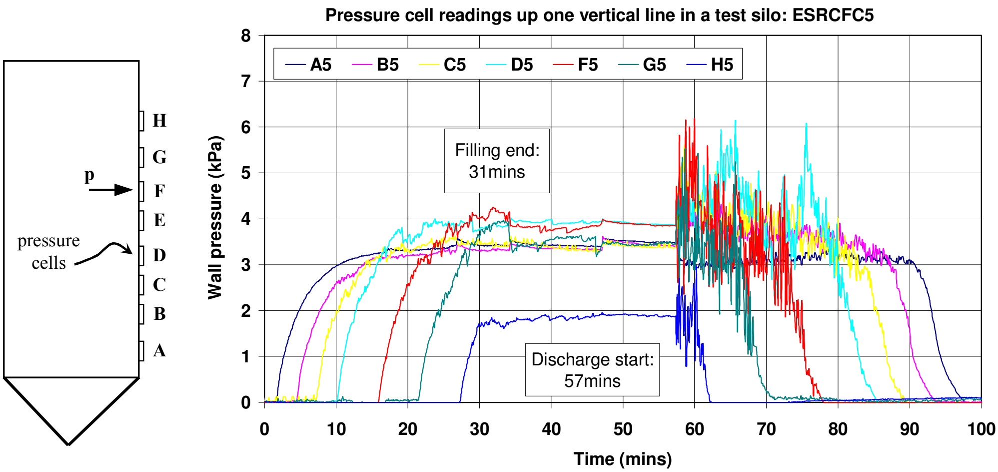
d) Older concrete and newer steel silos, France

e) Salt storage with control room, Italy

f) FRP farm silo, France

Figure 2: Different geometries and sizes of silo

However, the discharge loads on silos defined in all standards correspond to extreme simplifications of experimental measurements. These measurements (e.g. Figure 3) usually show a relatively stable set of pressures after filling and during storage, but very erratic behavior is observed during discharge. The physical explanations for these erratic pressures have been numerous, and a variety of quasi-static analyses have been offered in the past to try to quantify the magnitudes of the peak pressures. However, both computational modeling and analytical theories [1] currently do not predict the observed behavior, and do not provide a quantitative basis for silo design.



a) test silo b) measured pressures during filling and discharge

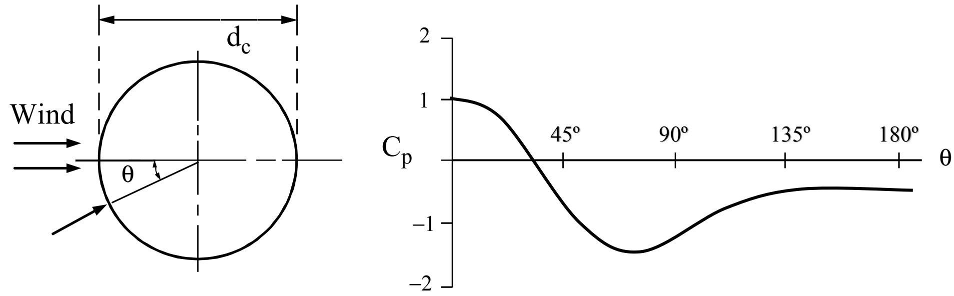
Figure 3: Typical experimental silo and trace of pressures on the wall

It may be noted that it is not simple to deduce what should be done with a test record like that in Figure 3. Traditional experimentalists have taken the highest observed pressure at each cell position and drawn an envelope over them, in the simple expectation that the highest pressure at each point must somehow be a worst case. Unfortunately this is far from the truth [20]. Unsymmetrical pressure patterns, even with low pressures, are far more damaging to the structure than uniform high pressures [18], so the actual patterns at different instants in Figure 3 need to be examined to determine the extent of loss of symmetry. This is a major task which the silo and shell structures research communities are only beginning to address. Moreover, the major loss of symmetry in silo pressures appears to be completely missing in all computational models for silo pressures to date [1].

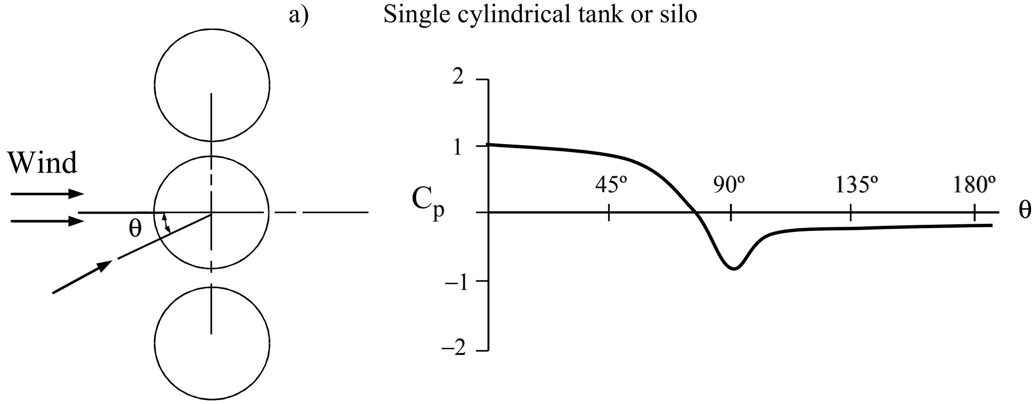
2.3. Wind and partial vacuum loads

During discharge of a tank or silo, inadequate venting of the airspace above the stored materials can lead to a partial vacuum which the structure is not easily able to sustain. This is a relatively simple load case.

When a tank or silo is wholly or partly empty, it is very susceptible to buckling in a windstorm. The wind exerts a non-uniform pressure on the shell, with the stagnation pressure at the windward generator rapidly decaying away from that location around the structure (Figure 4a). The pattern of pressure has commonly been regarded in the past as a fixed distribution, but more recent research has shown that it depends on the aspect ratio of the complete structure [12], varies with height and is affected by the roof geometry [14]. Further, it is clear that a group of tanks or silos in a line facing the wind experience a much larger zone of inward pressure (Figure 4b), and this promotes buckling failures more powerfully. A further problem of wind loading occurs when a large set of shells in a rectangular block are subjected to wind. Recent studies [3] have shown that those situated at a corner of the group are particularly strongly loaded by the wind. However, the design standards (e.g. EN 1991-2-4 [4]) are far behind on these aspects and much additional research is needed to upgrade them.



a) Single cylindrical tank or silo



b) Group of silos or tanks

Figure 4: Typical wind pressure distribution on a cylindrical tank or silo

2.4. Seismic loads

Earthquakes pose different problems to both silos and tanks according to the principal geometry of the structure. Where the structure is elevated (as in Figure 1b, 1c, 2a, 2d and

2e), the structure and its contents behaves very much as an inverted pendulum, with a very large mass supported above a spring of well defined stiffness. The natural period of such structures is usually long when full, but the level of filling changes the mass radically, so it can vary far more than other structures. This variation is important in seismic assessments. However, the behaviour of the contents is less significant in this structural form.

By contrast, when a tank is ground-supported (Figure 1a), the phenomenon of sloshing of the fluid becomes critically important, and careful assessments must be made of the convective and impulsive pressures, together with additional pressures induced by the deformations of the structure (see EN 1998-4 [9]).

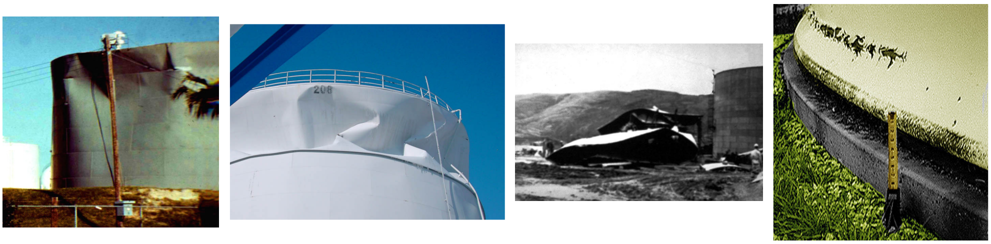
3. Failure modes in tanks

3.1. Introduction

The critical design considerations for a structure are chiefly revealed by the instances of structural failures. Here, the chief design problems in tanks and silos are identified by consideration of specific failure situations.

3.2. Buckling under wind and partial vacuum

The commonest failure mode in tanks is buckling under wind (Figure 5a), or under partial vacuum induced by rapid discharge of the contents or temperature reduction in the air above the liquid (Figure 5b). An inadequate tensile holding down detail at the wall base, where the deformable shell experiences greatly elevated local stresses, can cause complete loss (Figure 5c).



a) Windstorm buckling, USA | b) Partial vacuum, Finland | c) Tank separation from foundation, USA | d) Elephant's foot: seismic action

Figure 5: Tank failures under wind, partial vacuum and seismic action

3.3. Elevated metal tanks

Where a metal tank is elevated (Figure 1b), the junction between the storage vessel (usually a conical shell) and the supporting column is a point of discontinuity combined with high meridional compression and internal pressure. The conditions under which failure occur are relatively complicated and are described in the ECCS Recommendations [11].

3.4. Seismic failure modes in tanks

Ground supported tanks are particularly susceptible to failures under seismic action because of the sloshing behavior of the stored liquid. The commonest failure is an elephant's foot buckling mode (Figure 5d), involving plastic instability under higher pressures [15]. Accurate prediction of this failure mode depends chiefly on a careful evaluation of the acting pressures.

4. Failure modes in silos

4.1. Introduction and bursting

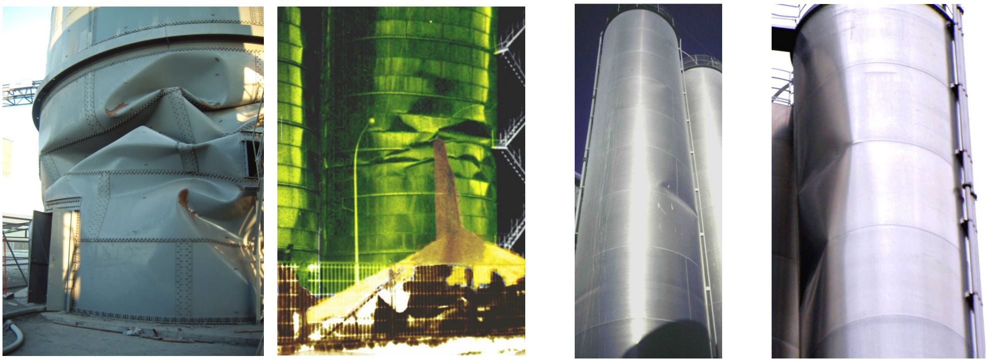
As for tanks, the chief criteria for silo design can be seen in the record of failure modes. As with a tank, the most obvious condition is internal pressure, but this rarely governs the design of a silo because vertical compressive forces in a thin metal shell are induced by both friction between the solid and the wall and unsymmetrical components of pressure. The latter also cause damaging local bending in concrete silos.

4.2. Bending in concrete silos

Unsymmetrical pressures in reinforced and pre-stressed concrete silos induce local circumferential bending of the wall, leading to severe cracking and sometimes to rupture. The most severe of these unsymmetrical pressure conditions is during eccentric discharge of the silo, when a channel of flowing solid against a small part of the wall causes very low pressures, with high pressures on either side. This condition was first codified in the new Eurocode EN 1991-4 [5], but less serious conditions also arise under apparently symmetrical flow (Figure 3), and these are currently dealt with using "patch" loads. The quantification and justification for the size, shape and magnitude of these patch load pressure patterns remains a significant research challenge.

4.3. Axial compression in metal silos

The commonest failure mode in cylindrical metal silos is buckling under axial compression. This failure mode is often catastrophic where it occurs under relatively symmetrical loading, but where locally elevated stresses cause such a buckle, it can be stable. Unsymmetrical pressures, and especially those associated with eccentric discharge, cause serious and catastrophic failures where the silo is sufficiently tall. Examples of such buckles are shown in Figure 6. This mode of buckling is very sensitive to the accuracy with which the structure has been built, so the new Eurocode EN 1993-4-1 [7] defines three Fabrication Quality Classes, which have different tolerance requirements and different defined strengths. However, for conditions of locally elevated axial compression, there is a significant dearth of knowledge and such failures remain slightly tricky to predict.

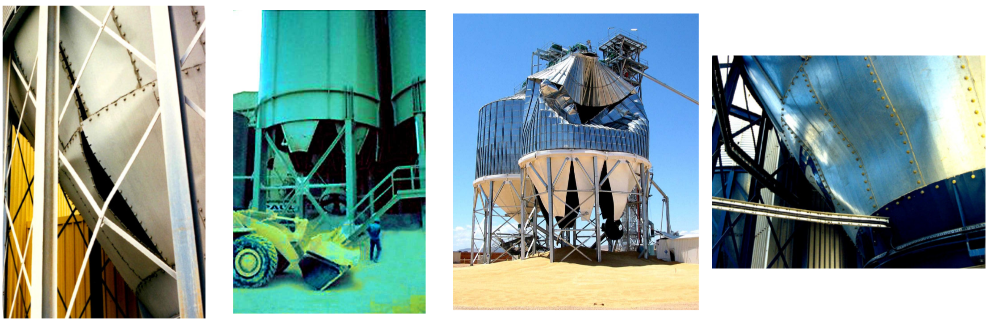


a) Uniform compression, Scotland b) Unsymmetrical compression c) Eccentric discharge, Scotland d) Eccentric discharge, Poland

Figure 6: Metal silo failures in buckling under axial compression

4.4. Wind and partial vacuum

When a silo is empty, the same problems arise as were described above for tanks. Tanks tend to be of larger diameter and thinner than silos, so wind buckling is commoner in tanks.



a) Hopper rupture, UK b) Hopper rupture, Germany c) Hopper rupture, Australia d) Hopper buckling, UK

Figure 7: Collapse of hoppers leads to total loss of the contents

4.5. Hopper collapse and buckling

The conical hopper in the lower part of a silo is there to facilitate discharge of the solids. Steep hoppers are needed when the stored solid is prone to the development of a small cohesion (e.g. flour). The silo is normally supported at the transition between the cylinder and hopper, putting the conical hopper into biaxial tension under both pressures and frictional tractions from the solid. Shells in biaxial tension are strong [16], and failures here normally only arise either because the solids pressures are badly misjudged or the designer has a poor understanding of shell theory. Examples of hopper rupture failures are shown in Figure 7. It is common for the roof or walls to be destroyed by the partial vacuum induced by the extremely rapid discharge of solids. Figure 7b also shows a buckling failure in a hopper, which is unexpected since the hopper is designed for biaxial tension. This type of failure arises either when structures connected to the hopper exert horizontal forces at the hopper base, or eccentric discharge flows cause unsymmetrical pressures, both of which lead to compressive stresses on one side [16].

4.6. Ring beam and support structure failures

The transition between the cylinder and hopper in a metal silo is not only a location of high circumferential compression due to the hopper tension, but it is also the zone in which local discrete supports are commonly introduced. These two roles lead to considerable complexity in the stress patterns, and lead most designers to exercise great caution. Both plastic collapse [23] and buckling failures [24] are possible, but the junction between a conical and cylindrical shell is a particularly stiff location, so simple analyses tend to underestimate the strength. Consequently, there are few failures, but there is great scope for an increased efficiency and reduced costs by using engaged columns [25] or bracket supports [2]. Much further research is needed to obtain good rules for design.

4.7. Differential settlement beneath silos and tanks

Both silos and tanks that are ground-supported are susceptible to buckling problems when differential settlements occur beneath them or adjacent to them. Such problems arise either because the tank or silo is built on land where earlier similar storage structures had caused long term settlement of part of the supported perimeter [10], or where only an adjacent silo is built too close at a later date and causes local settlements. This cause of damage is sometimes attributed when there is really a different reason, but it can be quite difficult to resolve such cases beyond all doubt. In metal silos, the consequent dimples appear to be relatively benign and not a cause for concern [10], but the consequent cracking damage to concrete silos can damage the stored product or cause leakage of liquid.

4.8. Seismic failure modes in silos

Elevated silos are similar to elevated tanks, and function as inverted pendulum structures. Ground-supported silos are less susceptible to failures under seismic action than tanks because a significant proportion of the forces exerted on the stored solid by horizontal accelerations are transferred directly to the ground [19]. This is a beneficial effect of the static frictional behavior of granular solids. The commonest failure is again the elephant's foot buckling mode (Figure 5d), involving plastic instability under higher pressures [15].

5. Current needs for research

5.1. Introduction

The above review of the critical loading and structural design considerations for silos and tanks indicates a number of vital areas for research over the next years. A few are highlighted here because of their critical importance.

5.1. Pressure characterization in silos

The structural design of a silo depends strongly on the pressure regime assumed to be applied by the stored solid. However, all current codes for design are based on very simple concepts and very approximate empirical rules derived solely from tests, and the tests themselves are extremely difficult to interpret [20]. Only a very few attempts have been made to perform statistical treatments of silo pressure measurements [13] and even then it is difficult to decide how to translate the outcome into useful design rules. Much further thoughtful research is needed in this area.

5.2. FEM or DEM quantitative predictions of silo pressures and solids flow

As noted above, current silo design is based on very empirical treatments of test records, because no computational models appear yet able to capture the phenomena seen in tests (Figure 3), let alone to quantify them well enough to give guidance on the development of better rules for design. Both continuum finite element and discrete element treatments have been used to try to overcome this problem, but to date the success has been rather limited. Research aimed at finding predictive techniques that can capture the phenomena, perhaps using stochastic variations of properties within a single body of material, would be most valuable and would represent a significant scientific advance in the field of granular solids.

5.3. Buckling in silos under local stress states

Most research on the buckling of metal shell structures has concentrated on simple load cases of uniform compression, uniform external pressure and uniform torsional shear, with further studies of global bending and translational shear [6]. However, many silo and tank structures are commonly subject to much more complex load cases, and it is possible to use nonlinear computational modeling to obtain good predictions for any given set of conditions [6]. The problem of imperfection sensitivity, and how it varies with stress state, imperfection form and amplitude [17] makes even these individual studies onerous. However, the generalization of these predictions into understanding and expressions suitable for design calculations is a challenging and complicated task, and much research effort is needed in this area in the coming years.

5.4. Locally supported cylindrical vessels

The support arrangements for elevated silos and tanks are currently designed more by experience than by science. In small structures, engaged columns and local brackets are used without significant calculations to justify them. In larger structures, such supports are rarely used, since the scientific basis is missing and designers err on the safe side. A significant research effort is needed here, but there are so many parameters that interact in determining the strength that such studies are far from simple [26].

5.5. Imperfection measurement criteria, methods and significance

The buckling strength of a shell structure is often very sensitive to minor geometric imperfections. In construction, these must be controlled to limit them to the values that have been assumed in the design process. This is particularly important now that EN 1993-1-6 [6] has permitted three quality classes of fabrication. But the huge range of different imperfection forms and their different effects on the strength of the structure make this control difficult to exercise. Current rules for tolerances in construction use crude methods of measurement, but are not yet calibrated against nonlinear computational assessments. Is a deep imperfection always bad? Does this dent matter? Much research is needed to bring together the science of imperfection sensitivity to tolerances measures needed in practice.

5.6. Relationship between tolerance measurements and strength

Current tolerance measurements do not relate well to computationally defined amplitudes of imperfections. Much work is also needed to establish the relationships between tolerance measurement systems and the corresponding strength. For example, it is insufficient to say that an eigenmode imperfection with amplitude of one wall thickness was used in design, since the constructor has no way of assessing how to make tolerance measurements that relate to a defect mode that he cannot see or assess.

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