ICBMH2023 - The 14th International Conference on Bulk Materials Storage, Handling and Transportation
11-13th July, 2023, Wollongong, New South Wales, Australia

Structural Failure of Silos: Learning Lessons from Failure

Prof Mike Bradley

Director, The Wolfson Centre for |Bulk Solids Handling Technology, Univ. of Greenwich,
London, UK M.s.a.bradley@gre.ac.uk www.bulksolids.com

ABSTRACT It is widely held that the occurrence of structural failure and distress of silos is much more common than other man-made structures (on a basis of per thousand structures per year). Such cases arrive on the doorstep of The Wolfson Centre with alarming regularity, for investigation.

In this paper, case studies will be used to illustrate various common and less-common causes of failure and distress that have been investigated. Conclusions will be drawn about improvements in practice that could be implemented to reduce the likelihood of such failures occurring.

1. INTRODUCTION

Mankind has been building bulk solid storage facilities for millennia, mainly to preserve grain between harvest and consumption. Modern silos as we would recognise them emerged in the mid-nineteenth century and ever since then, there has been a tradition of structural failure. In the early days this was mostly caused by lack of understanding of the loadings applied by the bulk solids. Only in the early 21st century has a sound, widely agreed and relatively comprehensive system of calculation emerged for “actions” applied to silos by the stored material, in the form of the silo Eurocode EN 1991:4 2006. In achieving this agreed code, and indeed its parent the Australian AS3774 code, we must acknowledge the outstanding leadership of Prof J Michael Rotter from Edinburgh University.

Yet in spite of this much improved position, silo failures remain extremely common. The author’s group at University of Greenwich on average receive two silo structural failures every year to investigate, and other specialists in the field around the world report similar. There are many individual causes, including design miscalculations, poor workmanship and inadequate maintenance, but also a significant contribution of ignorance amongst designers, as will be seen from the case studies in this paper.

2. UN-PLANNED ECCENTRIC DISCHARGE

Shown in Figure 1 is a case of distress on a bolted steel silo, typical of the effect of eccentric discharge in a metal silo where this has not been allowed for in the design.

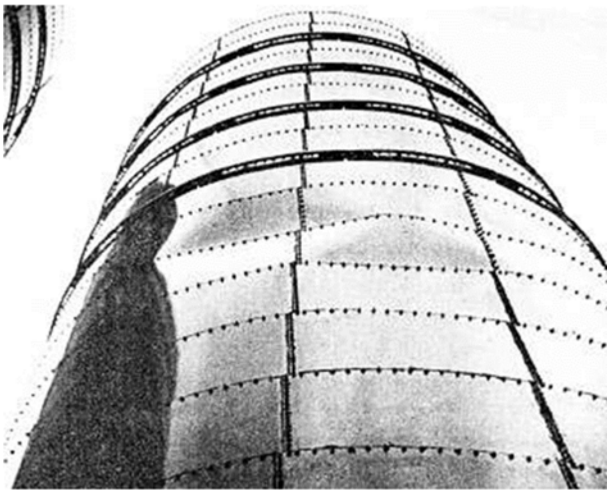

Figure 1 “Dint” in Silo Shell Due to Eccentric Discharge

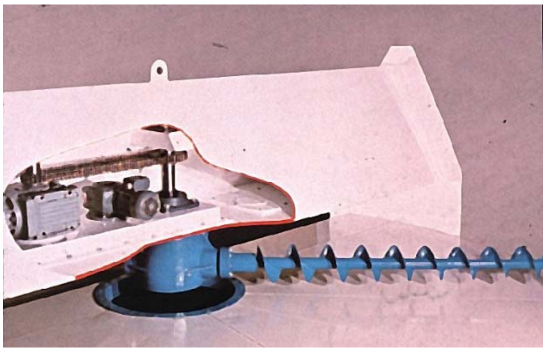

Figure 2 Typical Sweep Auger Discharger

This was a flat-bottomed silo discharged by a planetary screw discharger (Figure 2). This is designed to withdraw material from a radius at the bottom of the silo, but the screw progresses around the silo in order to give an effective mass flow pattern of discharge. At any given time, the discharge is only from one place around the silo and this gives an eccentric radial stress pattern but provided the sweep drive keeps moving the screw round, the effect is kept in check. In this case, the sweep drive failed, whilst the screw rotation continued. This let to a fully developed eccentric stress pattern through the height of the inventory. Where material flows down the wall, stress is greatly reduced, and its load transferred to the stagnant bulk solid adjacent to the flow channel, putting a bending moment into the silo shell. The result was the distortion shown in Figure 1 where the bending moment has locally pulled the shell into a straight line. This normally occurs in the top half of the silo, because the plates here are thinner than lower down and therefore much more susceptible to bending. Modern silo codes provide for calculation of this effect, so that it can be countered (usually most economically by use of ring stiffeners), but the designer had not considered eccentric discharge to be a possibility. The destructive effect of unplanned eccentric discharge has been seen for many other reasons so it must be included in the design, even if the possibility is small.

Designing for the effects of eccentric stresses on a cylinder is no easy task; it often requires FE analysis, but the competence of the FE user is critical to the security of the outcome.

3. USE OF INAPPROPRIATE CODES

In one case of a large wedge shaped silo of some tens of thousands of cubic metres capacity, the horizontal reinforcing beams running along the sloping flanks were showing some outwards bowing between the supporting struts. Discussions with the structural designer revealed that the actions on these sloping sections had been calculated using the code for retaining walls, the designer being unaware that the code for silo design would have been more appropriate. The retaining wall code does not include for the flow of the material which happens in the silo, which increases the lateral loadings considerably. Experience shows that many structural engineers of even the most senior level that work in general practice, are unaware of the special calculation methods required for the actions on silos.

Figure 3 A Large Wedge-Shaped Linear Silo

4. QUALITY CONTROL ON ASSEMBLY

With any silo assembled in the field, whether welded or bolted, it is vital to ensure that the assembly procedure is properly specified, followed and checked.

Many steel silos that are assembled by bolting, have joint designs that are not compliant with available bolted joint codes. This is because the codes for bolted joints have mostly been derived to cover design of bridges and steel building frames, which use relatively thick plate sections, whereas silos use much thinner plates than these codes cover.

A common feature of bolted joints in thin plate is that they rely on friction between the plates, as well as “bearing” of the bolts in the holes, to carry the joint load as shown in Figure 4 below:-

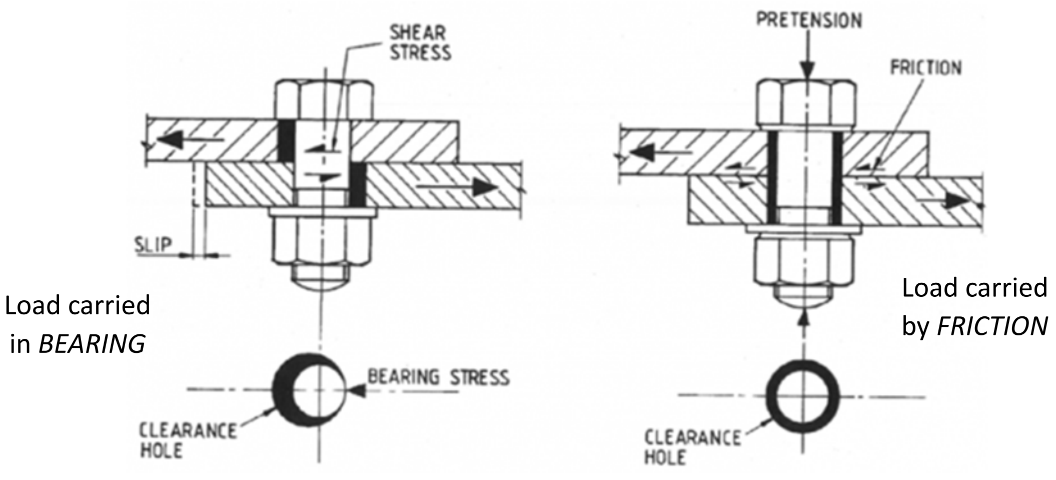

Figure 4 Extract from EN1993-1-3:2006 Showing Load Transferred by Bearing and by Friction

Silos of even some hundreds of tonnes capacity are commonly made from steel plate as thin as 3 to 5mm, especially in stainless steel which has a high tensile strength. But in such thin plate, there is little resistance to "shear-out" failure if significant load is transferred by bearing:-

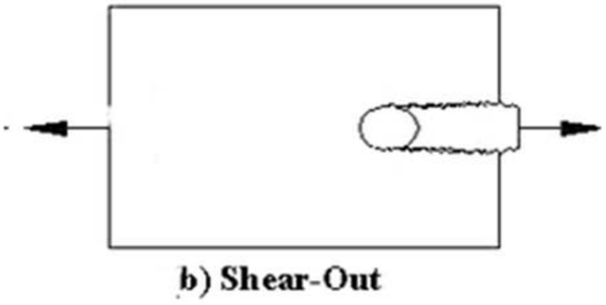

Figure 5 "Shear-out" Failure of a Bolted Joint Under Excessive Bearing Load

If the bolts are not tightened adequately, the strength of the joint is reduced by the lack of friction between the plates. The situation is further complicated by the fact that whereas shear-out failure can be predicted quite accurately for the thick plates generally covered in the bolted joint codes, it is much harder to predict accurately in the thin plates used in silos. For example EN 1993-1-3 (2006) gives guidance on bearing strength, but for shear-out load recommends testing a sample joint. Even if the designer happens to have allowed for the joint to carry the calculated loads in bearing alone, a lack of friction due to inadequate bolt tightening removes the additional robustness that fully tightened bolts would add to the joint, that would help it to resist unplanned overload – for example arising from eccentric discharge caused by discharging through a partially-open outlet valve, which can happen.

When it comes to assembly in the field, adequate supervision and checking of bolt tightening is critical. All bolts should be of a "high strength friction grip" specification, torqued to the proper design value, giving due consideration to presence or absence of lubrication or surface treatment, and the design accounting for a coefficient of friction determined from testing. As will be described in the next section, even one single bolt not properly installed and tightened, can precipitate complete collapse of the silo.

5. SUSCEPTIBILITY OF SILOS TO PROGRESSIVE FAILURE

One particularly important feature of thin metal silos is that they are highly susceptible to progressive catastrophic failure, more so than most other structures. Taking the failure shown in Figure 5 above, the scenario needs to be imagined that one bolt alone is not tightened up, increasing the bearing load and starting a shear-out failure towards the edge of the plate. As the shear-out begins, the load carried by this hole reduces very quickly, substantially increasing the load on the bolts above and below. These bolts then display increased bearing load, initiating shear-out, shedding their loads to the bolts above and below them and so on until the entire seam comes "unzipped" as the bulk solid moves outwards sustaining the pressure on the plates.

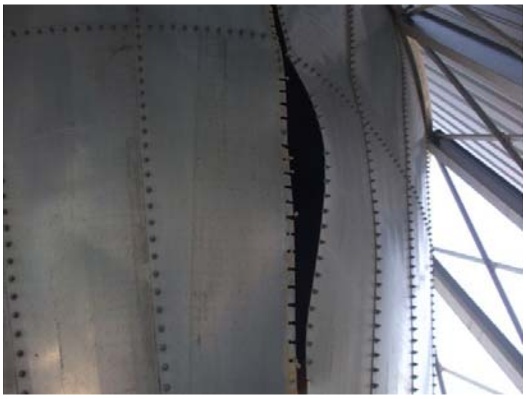

Figure 6 Progressive Failure of a Bolted Joint on a Silo Cone Involving Shear-Out of the Bolt Holes in Thin Sheet

This is due to the low stiffness of the thin plate; with joints in thick plate, if one bolt fails the load is evenly spread across the remainder of the joint, whereas in thin plate the load shed by one failed bolt is shared only between the ones immediately above and below, increasing their load by a factor of 1.5; given that the standard design factor of safety in the structural design code EN 1994 is 1.5, it only takes the loss of one bolt for its neighbours to negate that factor of safety. The view of the author is that the unique conditions that pertain with thin metal silos ought to demand a higher factor of safety on these bolted joints, to build in "robustness" – this will be addressed further later in this paper.

6. JOINT TESTING IN THE LABORATORY

The author has found it to be very useful during forensic investigations of bolted silo failures, to replicate short sections of the bolted joints, and pull these in a tensile tester to determine their strength, accounting for the quality of bolts used and the tightening torque. This is also to be recommended at a design stage if the joints used are not fully compliant with established joint design codes. Although there is a cost to this, it is much cheaper than a law suit over a failed silo.

7. FLANGED PANEL JOINTS

Joints between flanged panels have been seen to present a number of interesting challenges.

Figure 7 Failed Silo Constructed From Flanged Panels

One particular matter that sometimes appears to go unaccounted for in design, is the "prying" effect that magnifies bolt load in flanged panel joints due to rotation of the flanges under load so that they act as levers:-

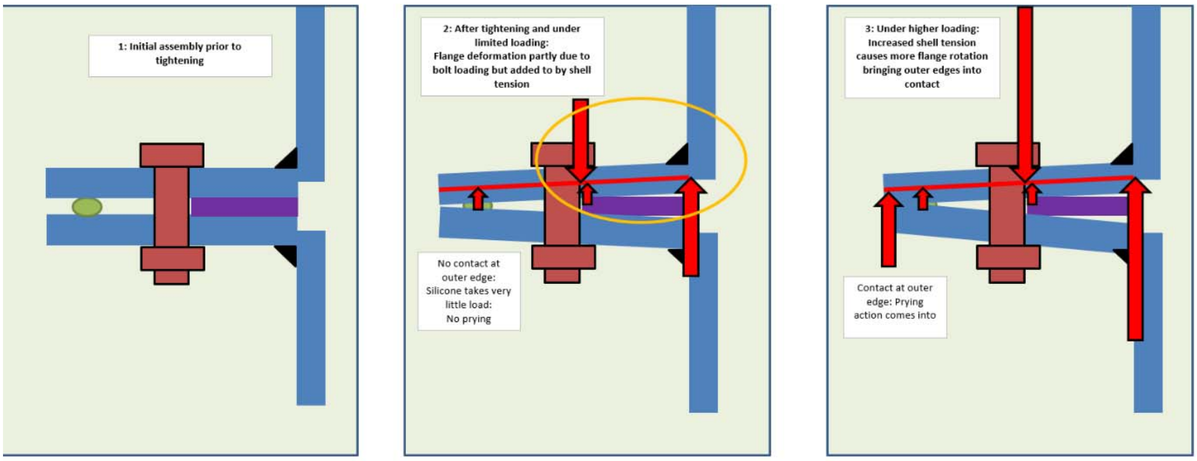

Figure 8 "Prying" Effect Magnifying Bolt Load in Joints Between Flanged Panels

Pulling tests on sections of such joints have shown bolt tensions amplified by a factor of as much as 1.8, well beyond the 1.5 factor of safety in EN 1994. Yet studies of some failures have shown the designer made no reference to this effect. The rotation of the flanges also puts very high loads and plastic deformation into the welds to the panels, in some cases leading to welds of nominally adequate strength being torn away from the face of the panels.

8. THERMAL RACKING OR "RATCHETTING"

"Thermal racking", first identified in the 1980s in Australia in the investigation of failures of large grain bins, has been seen in other silo failures. An investigation of a bin holding some thousands of tonnes of a fine powder implicated this as a contributor. The silo collapsed in the early morning, after having held the same quantity of material in static storage for some weeks with no signs of distress. The weather over the previous weeks had hot days and cool nights. This causes the silo to expand during the day, allowing the bulk solid to drop down a little, then when the silo cools and contracts during the night, it compacts the bulk solid, making it stiffer; over multiple cycles, hoop stress increases:-

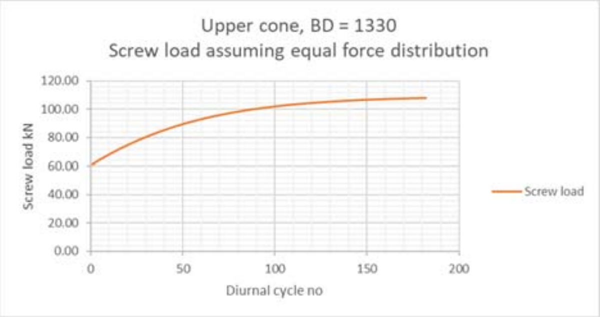

Figure 9 Model for Increasing Load in Screws Holding the Silo Panels Together, Due to Thermal Racking

In this case it was necessary for the forensic investigation, to devise a model for this effect. However, this could not be validated and the lack of an agreed, validated model for the effect of thermal racking is a serious omission from our ability to predict accurately the actions on large silos.

9. DESIGN OVERSIGHTS, MISTAKES AND SOUNDNESS OF CHECKING CALCULATIONS

Design code for structures, EN 1994, discusses supervision of designers, and checking of calculations to catch errors, indicating that the level (and independence) of checking needs to be commensurate with the consequence of failure. For a large silo where people may pass beneath, consequences are high and so should be the thoroughness of checking. However this does not always appear to be applied. In one investigation, the sizes of bolts specified for a bolted silo were a “non-preferred” size – a size that is standard, but not often used. This clearly indicated that there must have been some calculations done to arrive at that specific size, rather than a commonly used size. The silo collapsed due to failure of the bolts; calculations by the forensic team using the applicable codes showed that the bolts were of inadequate size for the strength class that had been specified – putting the bolt tension over the allowable limit if the silo was full, even without applying any factor of safety. The original calculation of actions appeared satisfactory, so how the designer then came to specify bolts of inadequate size is a matter of conjecture. Perhaps a miscalculation in a spreadsheet? Perhaps an oversight in not updating calculations between different sized silos of similar design? We will never know, but one thing is clear – diligent checking of the calculations would have caught this error, so it seems this was likely not undertaken as it should have been. It is a fact of life that every engineer makes mistakes, so the view of the author is that because silos put lives at stake, thorough checking of calculations by persons with the necessary experience in silos (not just a general structural engineer), independent of the designer, is appropriate.

10. OVERLOOKED EFFECTS OF DESIGN DETAILS IN BOLTED JOINTS

The high susceptibility of bolted joints in thin shells to progressive failure, means that “every bolt counts” in a silo structure. Every bolt must be looked at individually for its loading condition.

The consequence is that small details such as the increase in spacing of a single bolt pitch as shown in fig. 10 below, significantly amplifies the load on the adjacent bolts. In one investigation, this appeared to be the likely initiation of a progressive failure that led to complete collapse of a silo.

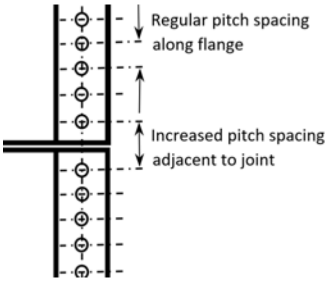

Figure 10 Inconsistent Vertical Bolt Spacing Local to Horizontal Joints, Amplifying Some Bolt Loads

Similarly, variation in the stiffness of the flange in a flanged-panel construction can also result in large amplifications of individual bolt loads:-

Figure 11 Flanged Vertical Joint in a Bolted Silo

The vertical flange is welded to the shell of the silo which is relatively thin, so the flange can flex under tension. But at the top end, the vertical flange is welded to the adjacent horizontal flange, making it much stiffer. So when the hoop stress tends to pull the flange apart, the top bolt carries much more load than the others.

Again, depending on how stiff the flanges are, this can lead to the top bolt here being loaded over its capacity whilst the ones below share much less load, again initiating progressive failure down the joint.

11. AVOIDABLE LACK OF ROBUSTNESS IN OVERALL DESIGN

The term “robustness” in structural engineering refers to the ability of a structure to avoid large-scale collapse when one part fails; the ability to redistribute load that is shed by the failed part, to other adjacent members that still remain within their stress limit. This avoids, or intercepts, progressive failure. A very well known example is the use of multi-strand cables instead of chains for suspension bridges; “a chain is as strong as its weakest link” so when one link or pin joint fails, the whole bridge collapses as in the well known case of the “Silver Bridge” collapse of 1967 in which a defect 2.5mm deep in a pin led to the death of 46 people [i]. By contrast, more modern suspension bridge designs use multiple-stranded cables, introduced by Roebling on the Brooklyn Bridge [ii], in which the failure of any one strand redistributes its load onto many more strands which remain within their stress limit.

As mentioned in section 5 above, joints in the thin shells of metal silos, whether bolted or welded, are highly susceptible to progressive failure. But in addition, with silos there are many uncertainties and difficulties in prediction of actions, which make the initiation of failure likely. So therefore it is logical that the overall structure ought to be designed in such a way that robustness is built in. Sadly, this is not always the case and designers often miss opportunities to provide robustness in silo designs.

One particular factor that needs to be highlighted is intelligent layout of panel joints; this can provide places where progressive failure can be intercepted, to avoid complete collapse of the structure.

Figure 12 Aligned Vertical Joints Encourage the Spread of a Progressive Failure

Figure 13 Staggered Joints Will Intercept Progressive Failure

As shown in fig. 12 above, the alignment of vertical joints means that if a failure starts in the vertical joint between two panels, it will inevitably continue to progress up and down that joint until the load is removed by release of the silo contents. By contrast, if a failure occurs in a vertical joint in the silos in fig 13, it will spread up and down that individual panel joint but the lateral offsetting of the vertical joints means that the “bridging” effect of the panels above and below the failed joint will prevent the failure from spreading further. The trends for aligned or offset joints appear to be regional; most bolted silos in the UK use offset vertical joints, whereas in mainland Europe, aligned joints seem to be favoured; in other part of the world including the US, it seems to be random between different manufacturers.

12. OVER-PRESSURISATION

Fig. 14 below shows a silo from which the top cone and the topmost ring of the barrel have been blown off, displaying shear-out failure of the bolted joint to the ring below. The silo top landed right next to the pressure-discharge road wagon operator, who was lucky to avoid serious injury.

Figure 14 Silo With Top Blown Off Due to Over-Pressurisation. The Top Cone and Ring of the Silo Are Lying in the Bottom of the Picture

This occurred just after starting pneumatic discharge of bulk solid into the silo, and resulted from a blocked filter. The filter was crude, a hessian sack tied over the bottom of a vertical pipe down the side of the silo. This had functioned for some time but the dust had gradually built up inside the sack, unseen from the outside, until it blocked the fabric and caused the silo to overpressurise. The over-pressure relief valve, in common with many used on silos, was not large enough to vent the volume of air delivered by the wagon blower.

There is comprehensive guidance available on avoiding such a hazard [iii], however experience shows that this type of occurrence remains quite common because of lack of implementation of the recommendations therein.

13. WORKMANSHIP IN THE MANUFACTURING SHOP

Investigation of the total collapse of a 200 tonne grain bin after 20 years of service revealed a fatigue failure in the sheet along a bend at the top edge of a cone segment, just below the joint to the barrel. The typical signs of metal fatigue were present – a significant part of the fracture area was dirty and corroded where the crack had developed and slowly grown, until the remaining area of sound metal could no longer support the load and failed in direct tension. The inevitable progressive failure occurred, with the cone tearing completely off the silo and the sudden down-movement of the contents sucking in the barrel above.

The cause of the cracking was obvious on the recovered parts – the bend had been made with a sharp-edged tool in the press-brake instead of a radiused tool, leaving a score-line in the surface of the sheet which initiated the crack.

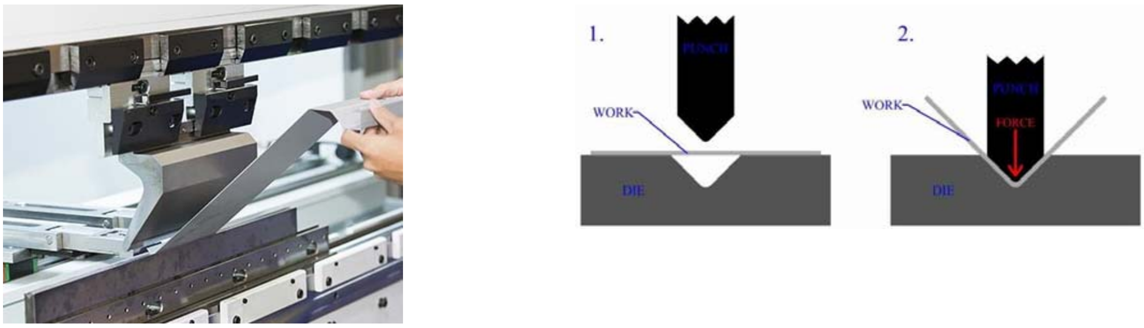

Figure 15 Bending Sheet on a Press-Brake; the Tool Edge Should be Radiused, Not Sharp

This is such a fundamental manufacturing error; the author remembers, as a 15 year-old apprentice being first instructed in the use of the press-brake, always to respect the necessary bend radius by means of a protector over the sharp edge of the tool. This demonstrates graphically how inadequate training of craftspeople, and inadequate inspection of workmanship prior to sign-off of QC in the shop, can lead to small but important detail problems in turn causing major and potentially fatal accidents. Such critical issues need to be identified, and checked in manufacturing QC.

14. UNEXPECTED HANG-UP THEN DROPPING OF MATERIAL

Several cases have been investigated where a bulk solid that had been expected to be free-flowing turned into a solid cake in the barrel of a silo, then eventually dropped suddenly into the empty cone below; in one case tearing the cone off, in other cases sucking in the barrel or the top plate of the silo. In one case this was the result of thermal racking compressing and consolidating relatively soft plastic pellets in residence for a long period through a hot summer, to make a caked mass. In another case it was the effect of moisture ingress from ventilating air, introduced just below the hip, causing caking in fertiliser pellets above in long term static residence. Whether this could happen needs to be considered at an early stage of design; the incorporation of generous FoS in the cone design should then be advised.

15. SKIRT BUCKLING

Skirt-supported silos present an interesting challenge to the designer; unlike the silo barrel, the skirt is not held in shape by the radial pressure of the bulk solid, so any small imperfections can greatly increase its susceptibility to buckling. Any uneven support of the skirt also brings great danger, not accounted for in codes, and the inevitable need for access doors to get to equipment under the cone, only makes the problem worse.

Figure 16 Steel silo with buckled unstiffened skirt

Figure 17 Aluminium silo on load cells, with buckle above stiffeners

Weld distortion can also make the situation worse, not only by introducing critical imperfections in the shape of the skirt, but also building in stresses. In the case of the aluminium silo in fig. 17, it was standing on three load cells so the designer was aware of the uneven load distribution that could cause problems with the skirt. His solution was to weld vertical stiffeners to the skirt above the load cell positions to distribute the load up the skirt. However, there were a number of problems with these. First, the stiffeners were continuously welded, meaning that shrinkage introduced a very high vertical compression in the skirt locally, thereby concentrating the vertical load into areas around the top of the stiffeners. Secondly, the stiffeners did not reach up to the hip but stopped at an unstiffened position part way up the skirt, where the sheet of the skirt could easily distort inwards or outwards with little restraint.

The advice of this author is that unstiffened skirts should be avoided on all but small silos, due to the unknowns involved in buckling. Even for small silos, if they stand on load cells, unstiffened skirts are a risk unless they have a very stiff circular beam around the bottom that distributes the load evenly around the skirt. Vertical stiffeners should be used, that should reach at least up to the ring beam at the hip, designed to act as fully supporting legs in their own right (braced where necessary) so the skirt has no other role than to keep the weather out of the space beneath the silo. Where stiffeners are welded on, they should always be stitch-welded (ie discontinuous welds) so that the shrinkage stresses can dissipate in the spaces between the welds. Sealing against water ingress is required, to avoid corrosion.

16. CONCLUSIONS

This paper has given a very brief tour of some of the causes of silo structural failure commonly seen in the authors' personal experience. It is by no means a comprehensive study of all the things that can go wrong. It should also be said that in many of the cases outlined, failure occurred because more than one of the factors discussed happened to occur simultaneously. However, as a result of these experiences there are certain points of advice that the authors would like to offer to silo designers, manufacturers and users, to minimise the chance of being caught out by unexpected problems:-

1) Always expect a chance of ***unexpected eccentric discharge***, whether due to feeder malfunction, caked material causing partial blockage or other causes, and design according to the actions in the code for this, unless you can show beyond reasonable doubt that eccentric discharge cannot occur.
2) Be cautious about the calculation of the load bearing capacity of ***bolted joints in thin sheet***, especially their reliance on friction within the joint. The authors believe that the usual factor of safety value of 1.5 commonly recommended in codes is inadequate for these, for the reasons explained, and would strongly recommend use of a FoS of 2 or preferably 2.5.
3) Be extremely diligent in considering the behaviour of joints between ***flanged panels***; the prying effect and flange stiffness variation can hugely increase individual bolt loads
4) If in any doubt over the strength of a bolted joint design, due to non-compliance with codes, ***make up a faithful replica and pull it in a testing machine*** to validate its strength. The cost of doing this is small, compared to the constructional cost of a silo of any substantial size.
5) Remember that ***EVERY BOLT MATTERS***; always be aware of the danger of progressive failure if just a single bolt is improperly tightened, or becomes overloaded for any reason - for example inconsistent spacing along a joint. Again consider using a higher FoS if in any doubt.
6) Build in ***robustness*** against progressive failure of joints, for example by offsetting the vertical joints in both cone and barrel
7) Avoid the use of ***unstiffened skirts*** on all but the smallest silos
8) Be aware of ***dynamic motion*** of large bulks of caked material, if there is a chance of the material caking at any time
9) Ensure ***calculations are fully checked*** by someone who understands the calculation methods, to ensure the right codes are used, and avoid errors or misjudgements
10) Ensure ***quality control in manufacturing and assembly*** is correctly specified and thoroughly undertaken, to avoid under- or over- tightening, misaligned holes, scored bend lines or too tight a bend radius, excessive weld shrinkage, use of correct strength bolts, bolt lubrication if required, appropriate washers etc. Just one detail overlooked can cause a catastrophic progressive failure.

In addition, it is clear that more research is needed in some of these areas, especially in regards to thermal racking and joints in thin sheet.

17. REFERENCES

---

[1] Witcher, T. R. (December 2017). "From Disaster to Prevention: The Silver Bridge" (PDF). *Civil Engineering*. Reston, Va.: American Society of Civil Engineers. Retrieved 2018-01-04.

[2] Talbot, Jim (June 2011). "The Brooklyn Bridge: First Steel-Wire Suspension Bridge" (PDF). *Modern Steel Construction*. Chicago: American Institute of Steel Construction. Retrieved 2018-01-04.

[3] Mineral Products Association, ”Guidance for prevention of storage silo overpressurisation during road tanker deliveries of non-explosive powders”, 2022, https://www.safequarry.com/hotTopics/MPA%20SPS%20Booklet%20updated.pdf retrieved 28 April 2023