Violent Failure

Hidden Causes for Destruction of a Grain Silo

G.E. Blight and B. Hoogendijk, South Africa

The sudden destruction of a silo at a grain depot in South Africa posed a number of questions. In-depth examination of the silo remains and detailed analysis showed that the silo failure was not caused by structural weakness, but by a 'hidden' dust explosion.

Early on the morning of August 12, 2009, a truck was standing in the loading shed of a small grain depot in rural South Africa (Fig. 2), with the driver sitting in the cab and a worker shoveling grain in the body of the truck. Without warning, the silo closest to the camera in Fig. 2 (silo no. 1) failed violently, flattening the loading shed, killing the unfortunate worker and strewing the grain contained by the almost full silo over a radius of 50 metre.

Fortunately, although the cab of the truck was partially flattened, the driver survived with only minor injuries. Fig. 1 shows the scene after the failure had occurred, with the skeleton of the silo roof in the centre of the field of view, on top of the remains of the silo, and the spread-out remains of the upper parts of the walls that had been projected away from the silo to the left and right.

1 Failure Description

Fig. 3 shows the short stubby remains of the silo, surrounded by spilt grain. From this view it can be seen that the internal stiffeners of the bolted corrugated sheet steel walls had been forced outwards as the upper wall sections parted from the lower part of the silo.

The section of wall leaning between the two silos had been flung violently against the neighbouring silo, indenting its walls with impressions of the bolt-heads in the failed portion which,

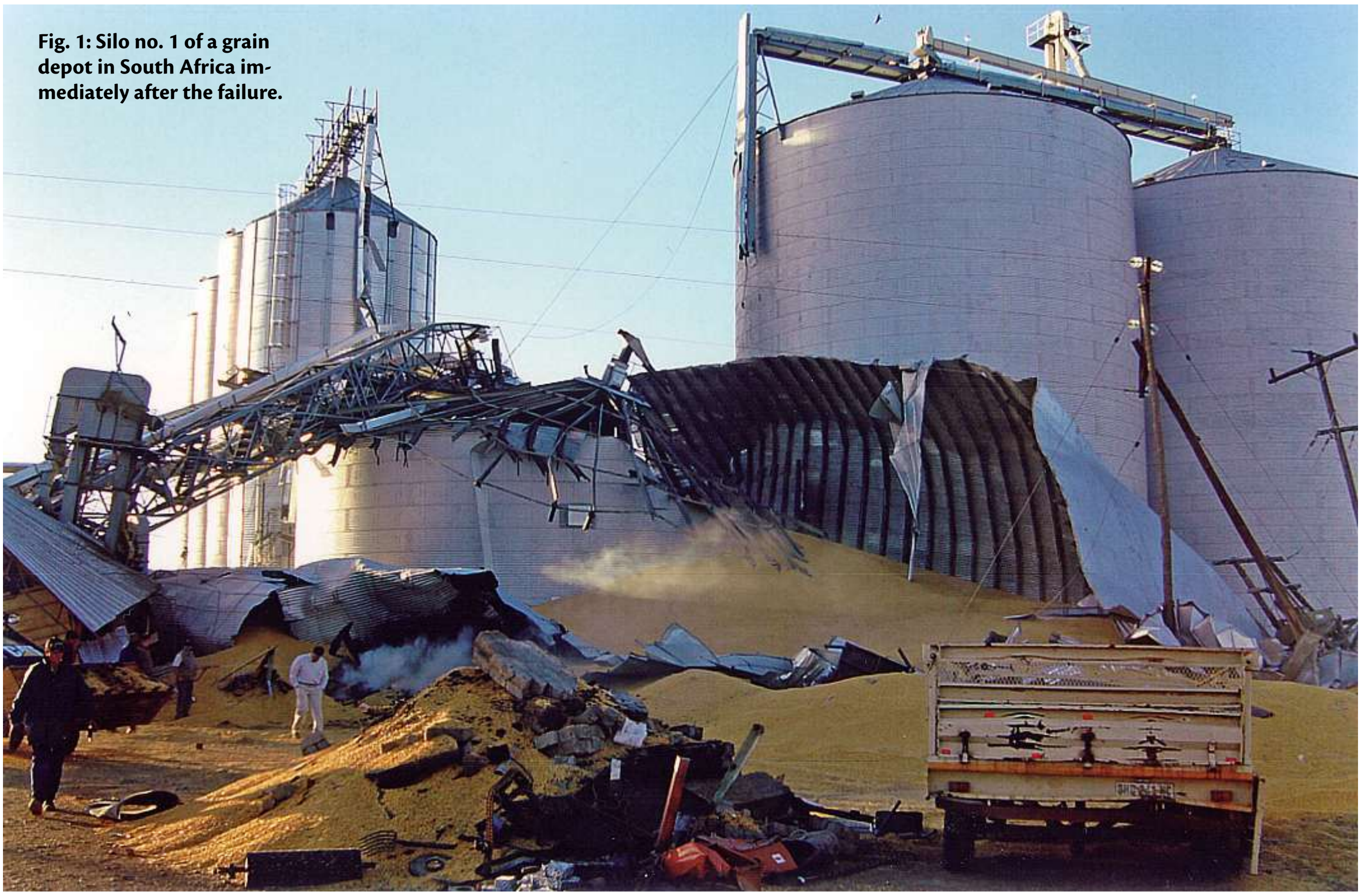

Fig. 1: Silo no. 1 of a grain depot in South Africa immediately after the failure.

Fig. 2: The silo complex before the failure.

Fig. 3: Remains of silo no. 1 viewed from opposite side to Fig. 2.

in turn, showed indentations of bolt heads from the neighbouring silo.

The detached portion of the silo wall had split from top to bottom in two places, almost diametrically opposite each other, and had partially split in a number of other places, one of which can be seen in Fig. 1, lining up with the centre-line of silo no. 2, to the right.

This is where, in clearing up the wreckage, the section of upper wall, seen remaining in Fig. 3, had been detached from the piece to its right in Fig. 1.

Fig. 4 shows the line of detachment that lay at the extreme right in Fig. 1. It can be seen that the wall plates all failed in a combination of tension and bearing.

Fig. 5 shows part of the diametrically opposite line of detachment. Here, some of the plates had obviously failed in bearing where a splice had been made across one of the top-hat stiffeners. Examination of Fig. 4 will show that every second plate was also spliced across the stiffener at this location and appears to have failed in the same way.

2 The History of the Silo

The large silos shown in Fig. 2 (18.19 metre in diameter and 23.69 metre in height of barrel) as well as four smaller (9.15 metre diameter) silos had originally been erected new, 25 to 30 years previously, at a different location.

An identical 18.19 metre diameter silo had been instrumented with strain gauges at about that time, and strains had been measured during filling and emptying with maize. The results of these measurements were published by Blight in 1989 [1]. Hence the functioning of the structure was well understood.

As a result of changes in crops in the area, the silos became redundant, and were sold, dismantled and moved to their present site where they were re-erected and in operation in 2004. There was a change of ownership in 2005.

In their new location, two crops, one of wheat, the other of maize, are harvested each year and the re-erected silos had been used to store both wheat and maize harvests since 2005. Hence the re-erected large silos had been 'proof-filled' many times before the failure occurred.

However, one of the smaller silos (silo no. 4 the one closest to silo no. 1) had collapsed in 2008 and had to be replaced. In an inspection of all of the silos following this failure, it was discovered that during re-erection of the silos, stiffeners with incorrect thicknesses had been used in various places, and these were all strengthened appropriately.

The inspection also revealed that in the large 18.19 metre diameter silos, plates having different thicknesses had not been correctly located. Specifically, in the large silo (silo no. 1) that failed catastrophically, the thicknesses of the rings should have been 1.6 mm from ring 1 at the top of the silo down to ring 14, 2 mm for rings 15 to 17 and 3 mm for rings 18 to 31, at the base of the silo.

Instead, for silo no. 1, rings 1 to 13 were correct (1.6 mm thick), but ring 14 had 2 plates of 1.6 mm and 8 of 2 mm, all 10 plates of ring 15 were 1.6 mm thick, ring 16 had 8 of 1.6 mm and 2 of 2 mm and rings 17 to 31 were (correctly) 3 mm thick.

3 Possible Failure Mechanisms

The two largely intact pieces of upper wall seen in Figs. 1 and 3 extended down to ring 13, while the top of the stub of silo was generally at ring 22. After the clean-up of wreckage, rings 14 to 21 were 'missing'. Actually, they were unidentifiable, being in a mixed pile of wreckage recovered from the failure with no attempt having been made to mark their origin.

Fig. 6 is a developed elevation of silo no. 1 showing the relative positions of the two largely intact segments of upper wall, the remaining stub of the silo and the 'missing rings' in between. Fig. 7 is a plan showing the positions of silo nos. 1, 2 and the reconstructed silo no. 4 and the lines (A1 – B1 and A2 – B2) taken up during the failure by the lower end of the two segments of upper wall.

After the failure, both of these wall segments leaned towards the original position of silo no. 1. As the missing rings included the three under-strength rings 14, 15 and 16, it was initially thought that the failure must have originated in the under-strength rings and that it was caused by the lack of strength in this locality. However, it was also known that silo no. 1 had successfully stored and been emptied of both wheat and maize harvests since 2005, without any signs of distress.

From experience with other bolted corrugated steel silos, it would be expected that if one or two under-strength rings had failed in tension or combined tension and bearing, as appeared might have happened, it would not have led to sudden catastrophic failure.

The effect would have been local. A split would form, some grain would run out, locally relieving the pressure and the process would stop without causing collapse of the silo. As an example, the maize in an almost identical silo caught fire a few years ago. In the absence of fire-fighting equipment, an opening was made by cutting through the two bottom rings of the silo, and the maize was raked out of the opening to empty the silo and extinguish the fire.

The complete severance of the two nominally most heavily loaded rings in the silo had no noticeable effect on the structure. See page 198 of [2] for a photograph of this silo showing the hole cut in the otherwise intact silo.

In the present case, two similar holes, diametrically opposite each other, were cut in the stub of silo no. 1 to empty out the remaining grain.

Calculations also showed that if the overall load-bearing capacity of the three under-strength rings 14 to 16 together with the full strength rings 13 and 17 on either side was considered (a vertical height of 3.8 metre), there was sufficient strength available to carry the hoop tension, even if there were splices over a stiffener in every second ring, as shown in Fig. 4. There was considerable confidence in the calculated hoop tension because the calculation agreed with the range of hoop tensions measured in an identical silo [1].

Fig. 4: Line of rupture of wall to right of Fig. 2.

Fig. 5: Line of rupture to left of Fig. 3.

4 No Failure by Buckling

A possible failure by buckling of the stiffeners following the formation of a void below a hang-up in the grain was also considered, but rejected as this type of failure usually occurs in a completely non-violent manner, see, e.g. [3].

Figs. 2 and 7 show that the upper 13 to 14 rings were violently projected away from the silo, being straightened and translated in the process and falling with their outside faces uppermost. In height, the displaced lengths of wall appear to have been almost planar, but slightly curved towards the axis of the silo. The frame of the roof was still more or less in the same place in plan, but slightly displaced to one side.

As the wall stiffeners had been bolted to the roof, the walls must have been projected outwards and have simultaneously broken their attachments to the roof. It was also significant that there were two main vertical tension separations, separating and detaching the silo wall above rings 19 to 22 into two separate pieces.

When the problem of the missing rings was examined, it was at first thought likely that if one or more of the under-strength rings had suddenly failed in hoop tension, the stiffeners adjacent to the failure would no longer have been restrained in a radial direction and also failed suddenly by buckling.

However, calculated stiffener loads for the vicinity of the weakened rings 15 to 17 were about 180 kN which agreed with stiffener loads measured on the identical silo [1]. Calculated buckling loads for an unsupported stiffener ranged from 335 kN for an effective length of 1.5 metre (2 failed rings) to 240 kN for an effective length of 4.5 metre (6 failed rings). Hence buckling could be ruled out as a secondary mechanism of failure.

The two separations must have occurred simultaneously. If one separation, say A1 – A2 in Fig. 7, had occurred first, the hoop tension would have been released by the failure and the second failure could not have occurred. The only way in which hoop tension could have been retained in the wall would be by horizontal friction along the inside of the wall.

For this to happen, the angle of friction for horizontal shear parallel to the corrugations would have had to exceed $\arctan(2 \cdot \pi^{-1}) = 32.5°$. Even if the stiffeners had roughened the wall sufficiently to cause shearing to occur through the grain, the angle of shearing resistance of maize is 30° and insufficient to retain the hoop tension.

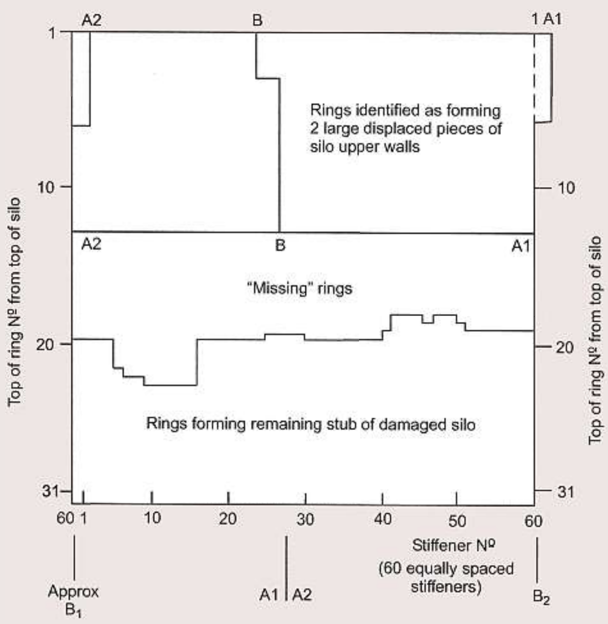

Fig. 6: Accounting for silo rings after the failure; view from outside of silo.

6 Probably a Dust Explosion

This calculation, together with the violence of the failure led to the tentative conclusion that the failure occurred as a result of a dust explosion. Many violent, destructive failures resulting from dust explosions have been recorded, e.g. by Ravenet [4].

At about this time (October 2009) a paper by Calil, Palma and Cheung appeared in Bulk Solids Handling, which contained a title page photograph showing a very similar failure [5].

The failure was said to have been caused by 'shearing of the joint bolts between the metallic sheets'. The similarities between this photo and Figs. 2 and 3 are striking. In both cases, the roof was dislodged, but landed close to its original position, and the stiffeners were bent radially outwards. The photo shows severe denting damage to two empty adjacent silos caused by the projected pieces of upper wall.

This damage was similar to the bolt head indentations suffered by silo no. 2 when silo no. 1 failed. Correspondence by email between the present authors and Professors Calil and Cheung resulted in confirmation that the failure in Brazil had been caused by a dust explosion.

It was then decided to carry out a model test to study the characteristics of a failure caused by an explosion at the top of a full silo. A model silo was built with the walls modeled by thin balsa-wood stiffeners covered by model aircraft paper. To model the change in ring thickness, the upper two thirds of the model walls was covered by a single thickness of paper, and the lower one third by two thicknesses.

The model was filled with uniform dry sand and a small fire-cracker was embedded in the top of the sand. To provide a reaction to the explosion, the top of the model was covered by a circular 10 mm thick plate of a slightly larger diameter than the silo. Fig. 8 shows the result of electrically detonating the cracker.

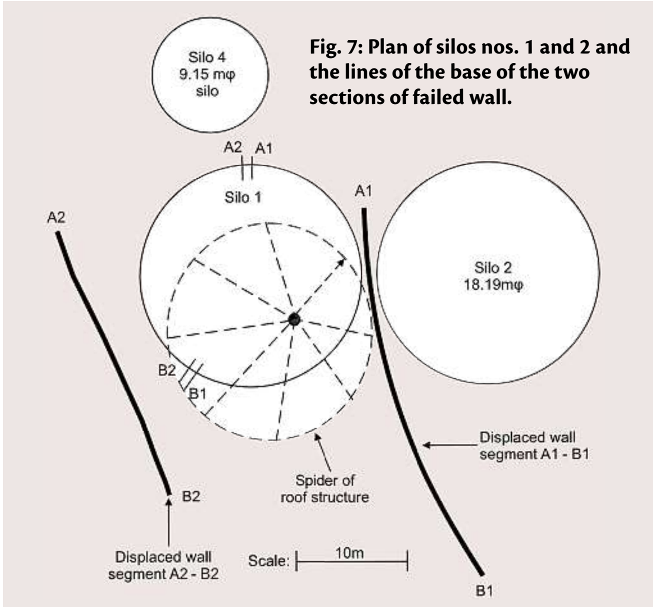

Fig. 7: Plan of silos nos. 1 and 2 and the lines of the base of the two sections of failed wall.

The upper two thirds of the walls were split in two diametrically opposite positions with some of the balsa-wood stiffeners being broken. The remainder of the model was relatively undamaged. Hence the effects of an explosion at the top of a full silo had successfully been reproduced in the model.

7 Final Calculations

The failure stress in tension on the net cross-sectional area of the rings would have been the yield stress in tension of 450 MPa. Taking the lateral pressure coefficient in the grain as one third, the blast pressure at the top of the silo required to cause yield in the rings was 210 kPa. This is well within the range of possible blast pressures caused by an explosion of maize dust of up to 600 kPa, according to Ravenet [4].

Hence it was concluded that the most likely cause of the failure was a dust explosion, triggered by a spark struck on the back of the truck while grain was being shoveled in it, or by the worker lighting a cigarette.

The explosion then struck up the bucket elevator, detonated dust in the air space in the roof of silo no. 1 and the ensuing explosion destroyed the silo.

8 Post Script

Operators of grain silos should be well aware of the dangers and possible effects of dust explosions, and that even a small spark might be sufficient to trigger a destructive event. However, it is very likely that workers visiting rural grain depots, either to load or off-load grain, are completely unaware of the potentially dangerous conditions in which they are working.

There is obviously a strong case for an induction procedure to be followed for anyone visiting a grain depot, just as there is for anyone visiting a coal mine or coal depot. ■

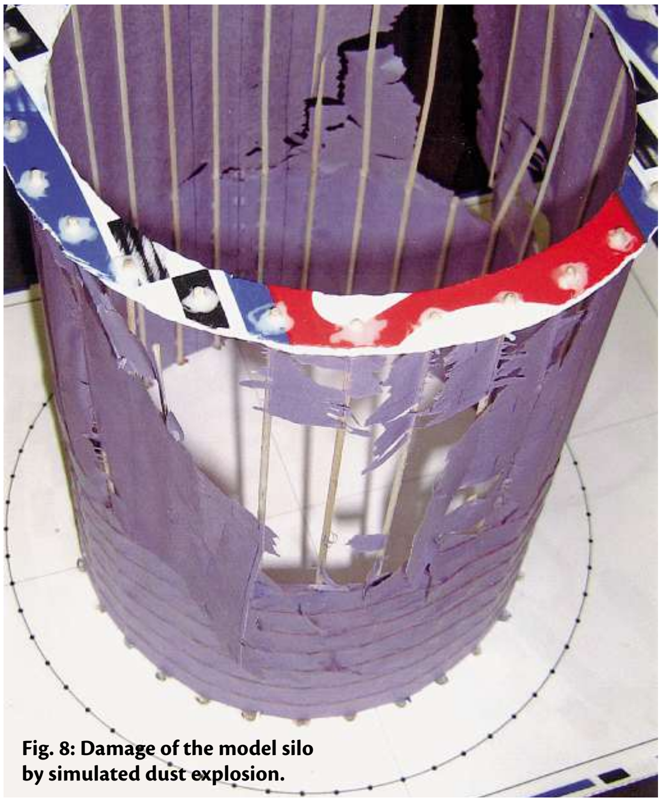

Fig. 8: Damage of the model silo by simulated dust explosion.

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[3] Blight, G.E.: *A completely symmetrical failure of a bolted corrugated silo*. bulk solids handling, Vol. 29 (2009) No. 5, pp. 272-276.

[4] Ravenet, J.: *Dust explosions in silos and plants, causes and prevention*. bulk solids handling, Vol. 10 (1990) No. 2, pp. 503-512.

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About the Author

Prof. em Geoff E. Blight

Geoff Blight is Professor Emeritus of Civil Engineering at the University of the Witwatersrand, Johannesburg, South Africa. He has studied the loading and load distribution on silos since the early 1970's and has published widely on this research. He authored the book "Assessing loads on silos and other bulk storage structures" in 2006.

Contact:
University of Witwatersrand
P.O. Box 3, 2050 Wits, RSA
Tel.: +27 (011) 717 7105
Fax: +27 (011) 476 8759
E-Mail: blight@civil.wits.ac.za

About the Author

Barry Hoogendijk (Pr. Eng.)

Barry Hoogendijk received his degree in civil engineering from the Stellenbosch University, South Africa. Before moving to Bessemer, he spent 23 years with consulting firms on site and in the office, mainly on the structural side. He is now in his 13th year at Bessemer, where his focus is on structural steel, grain storage and grain handling equipment.

Contact:
Bessemer (Pty) Ltd
P.O. Box 4102, Luipaardsvlai 1743, South Africa
Tel.: +27 (011) 762 5341
Fax: +27 (011) 762 5345
E-Mail: barry@bessemer.co.za