An investigation of out-of-roundness in partially constructed silos and tanks

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1. SUMMARY

This paper describes a project that seeks a better understanding of the influence of non-uniform support conditions during construction on the out-of-roundness distortions in both ground-supported and discretely supported thin-walled cylindrical silos and tanks. Distortions introduced when the shell is partially built become locked in, making subsequent parts of the construction more distorted, and a construction team's attempts to correct them may lead to further distortions. The erection contract may then be arrested, and the team's efforts to remedy the structure may dramatically increase the cost of the complete project. Such distortions during construction of shells with non-uniform support have been observed in several different countries.

A 1D Fourier decomposition was employed first to describe the deformations that arise in some laser-scanned silos in order to characterise the imperfection patterns and their correlation to the construction process. The phenomenon was then modelled using finite elements in ABAQUS and a parametric study was conducted to explore the influence of the various geometric parameters on out-of-round deformations. Regardless of the elastic behaviour that governs the performance of the shells, it is shown that very small local settlements on the lower boundary can introduce significant out-of-plane distortions.

2. INTRODUCTION

Shell structures are often the preferred solution in industrial civil engineering projects due to their ability to span relatively long distances, efficiently sustain a high incoming load as well as for aesthetic reasons. In particular in thin shells which exploit membrane action, a specific and highly efficient distribution of stress resultants provides both a stiff structure and a decreased use of material. However, the thin profile of these structures increases their vulnerability to deformations that may arise during the construction process. The focus of this project is thin steel silos or tanks on discrete supports during the erection process, a system commonly used in top-down construction. This construction method follows a specific sequence. The roof is first constructed and placed on a set of discrete jacks that raise it to permit the top strake to be installed. A "spider" with discrete spokes is used to maintain the circularity of the form. The curved wall panels of the top strake are then vertically welded to each other and circumferentially welded to the roof. The assembly is then jacked up again to permit the next strake to be inserted, and the process repeated until the complete curved shape of the silo is formed. However, in many cases excessive deformations develop due to the discrete support of the jacks, and these may finally lead to interruption of the construction. This is because even small vertical non-uniformities in the base boundary of a partly constructed cylinder can result in very significant out-of-plane distortions during construction. The same phenomena arise in more conventional bottom-up construction if foundation settlements develop during the erection process.

This project aims to present the mechanics that govern the deformations that may arise during the construction process of such thin steel silos and tanks, which are discretely supported or whose base vertical displacements are imperfectly restrained. This was achieved by examining some fully anonymised field measurements, supported by a parametric study conducted with the use of the finite element software ABAQUS [1]. The field measurements correspond to two partially constructed silos, which were supported on eight jacks. Their erection process was interrupted due to the significant geometric deviations that occurred. A parametric study was further conducted with the aim of identifying the effect of (a) different radius to thickness r/t ratios, (b) the number of supports provided and (c) the height of the panel affected by the axial (meridional) deformations that led to more serious radial deformations.

3. STATE OF THE ART

Research articles treating this phenomenon in discrete jack supported cylinders have not been found in any published study. The most relevant comparable studies concern the deformations that arise due to differential settlements. Malik *et al.* [2], appear to have been the first to examine the differential settlement of a tank caused by inadequate foundation support. They categorised the types of deformation into three groups: a) uniform settlement, b) centre-to-edge settlement and c) circumferential or differential settlement. They analysed the consequences using Fourier decomposition and estimated the ovality of the cylinders and their results were verified by experiments. The radial deformations of open-topped tanks, due to the differential settlements, were later studied by Kamyab & Palmer [3,4]. By expressing the profile of the differential settlements as a Fourier expansion, the corresponding membrane analysis was formulated, which can estimate the radial deformations according to the relative stiffness of the entire shell and the primary wind girder. They verified that this treatment is applicable to most practical cases and that the inextensional analysis of [2] retrieves valuable results only when the differential settlement is relatively smooth over large circumferential length. Furthermore, in [3] they formulated a set of charts that can be used to predict the maximum radial displacements according to the differential settlement of the foundation. Two years later, an experimental study was performed in order to verify the results derived from the membrane analysis [4]. The effects of geometric nonlinearity on the deformations in tanks under local settlement were studied by Hornung & Saal [5]. Since the most serious consequence of the resulting distortions is the reduction in buckling resistance, further studies of the loss of buckling strength caused by differential settlement were conducted by Holst & Rotter [6-8].

4. ELABORATION OF FIELD MEASUREMENTS

Field measurements made on two silos under construction were explored in this project. The scanned data from two partially-constructed silos (‘A’ and ‘B’), treated anonymously for reasons of confidentiality, were analysed. The construction of these silos was stopped due to the large geometric deviations that arose. The silos were scanned using laser telemetry. Three different stations around the circumference were used to obtain the data, leading to non-uniform spacings of the sample points both down the meridian and around the circumference, exaggerated by the curved shape of the structure. Both silos were supported on discretely located jacks so that the reference cylinder, relative to which the geometric deviations should be calculated, cannot be known in advance. To locate the position of the most appropriate cylinder, the ‘best-fit cylinder’ procedure proposed by [9] was employed. Further, since it was expected that the non-uniform spacing between the sample points would affect the accuracy of the Fourier decomposition, the *griddata* command available in Matlab [10] was employed. This command interpolates intermediate points and provides a uniform spacing between the sample points without significant loss of accuracy.

4.1 FOURIER ANALYSIS OF SILO A

The aforementiomed methodology was initially applied in the first silo, denoted as Silo A. The geometric features of the silo are listed in Table 1, while the deformed shape amplified by a factor of 100 is shown in Fig. 1, using the surface generated by the *griddata* command and containing all the sample points. The deviations from the best fit cylinder are small near the bottom and top edges but are largest at meridional coordinates between 4m and 8m. A specific pattern of inward and outward deformations around the circumference is also evident.

The uniformly-spaced sample points generated by the *griddata* command enable 1D Fourier decomposition to be undertaken without significant loss of accuracy. The decomposition was performed in the circumferential direction, at specific meridional coordinates. It is important to recognise that the maximum number of harmonics N_z that can be extracted from N_s sample points is limited [11] to $N_z \leq (N_s - 1)/2$. Figure 2 illustrates the harmonic amplitudes down the meridian of the shell, presented as the combined amplitude $D_j = \sqrt{(a_k^2 + b_k^2)}$ where a_k and b_k are the amplitudes of the k^{th} sine and cosine harmonic terms respectively. For reasons of clarity, only the harmonics with the highest amplitudes are plotted. Throughout the height of Silo A, it is evident that the amplitude of Harmonic 8 is significantly higher than the others. This is clearly related to the use of 8 jacks around the circumference to support the silo during construction.

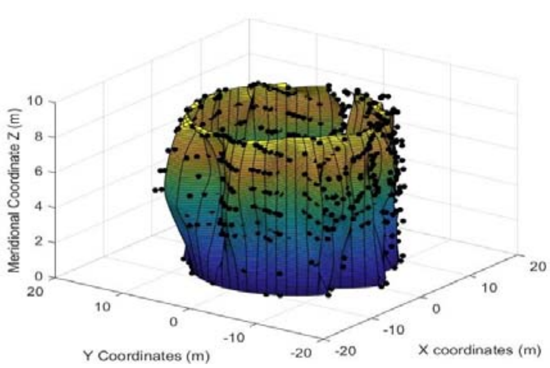

Figure 1: Amplified 3D plot of the griddata surface and the sample points.

Geometric Properties	
Radius (m)	12
Height (m)	8
Supports	8
Measured Points	772
Thickness	
0-4.2	8
4.2-8	6

Table 1: Geometric Properties of Silo A.

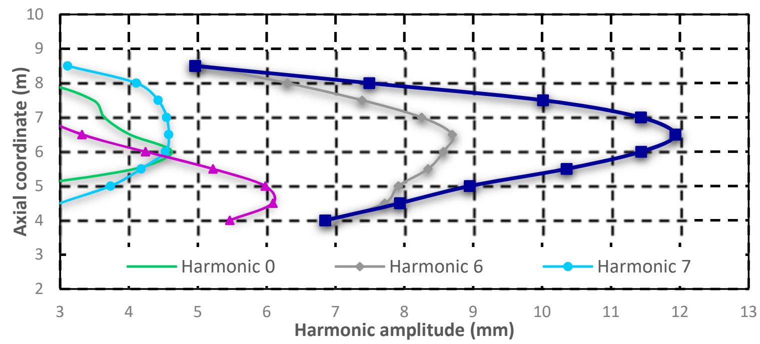

Figure 2: Amplitude of the harmonic terms along the meridian of Silo A.

The maximum normal deformation was 51mm (Fig. 1), observed at around 5.3m above the bottom edge and corresponds to 8.5 times the silo wall thickness at that location. Regardless of these large deformations, the silo can be categorised according to EN 1993-1-6 [12] as Fabrication Quality Class C using the criterion of dimple tolerances, though these deformations are unacceptable according to API 650 [13].

4.2 FOURIER ANALYSIS OF SILO B

The same methodology was applied to the measurements of the second silo (Silo B), whose geometric properties are listed in Table 2. A 3D plot of its amplified deformed shape is shown in Fig. 3. By contrast with Silo A, this silo was at a more advanced stage of construction where the roof had already been welded to the top edge. As was seen for Silo A, the geometric deviations are less significant near the bottom and top edges, while they are highest at approximately 75% of the wall height. A set of 1D Fourier decompositions in the circumferential direction was performed with a meridional spacing of 0.5m throughout the height of the silo.

The harmonic amplitudes with the highest values are presented in Fig. 4. For most of the height, the amplitudes of Harmonic 8 are significantly higher than the others. Again, the dominant harmonic and the deformed shape of the silo are mostly associated with the number of discrete supports provided around the circumference. It can also be seen that, above 11.5m, Harmonic 16 becomes the dominant one. This phenomenon occurs due to the welding of the roof at the top edge. The roof was constructed separately and was welded to the top of the wall at 16 discrete points. Because the 16 supports produced some distortion of the edge of the roof in the vertical direction, these distortions were transmitted as axial deformations into the top of the silo wall, leading to normal deformations of the wall in Harmonic 16.

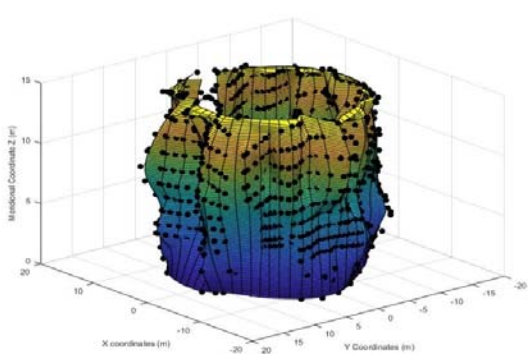

Figure 3: Amplified 3D plot of the griddata surface and the sample points.

Geometric Properties	
Radius (m)	12
Height (m)	14.8
Supports	8
Measured Points	1143
Thickness	
0-3.6	12
3.6-7.2	10
7.2-11	8
11-14.8	6

Table 2: Geometric Properties of Silo B.

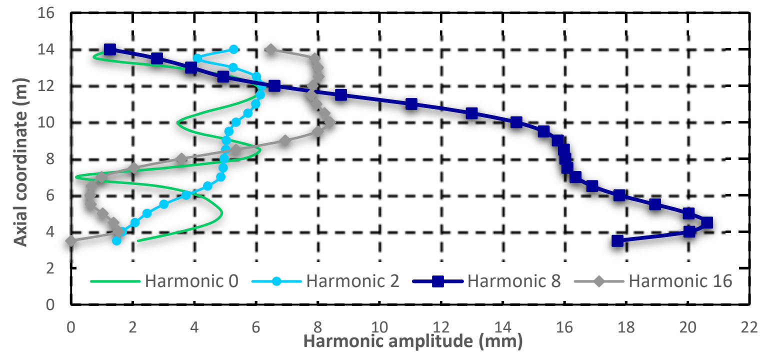

Figure 4: Amplitude of the dominant harmonic terms along the meridian of Silo B.

The maximum geometric deviation seen was 53 mm, located 12.2 m from the bottom at a point where the silo wall was only 6mm thick. The silo can still be categorised as Fabrication Quality Class C according to EN 1993-1-6 [12], though it is unacceptable according to the API 650 [13] specifications.

5. RESULTS OF THE PARAMETRIC STUDY

Next, the results of the computational parametric study are presented. The factors examined were: (a) r/t ratios in the range 1000-3000, (b) the number of supports provided (3 to 28), and (c) the height of the panel (1-6 m). During the erection process, the radial form of the silo is constrained by the spider with its radial spokes, which were modeled using discrete restraints of the translational dofs in the radial, circumferential and meridional directions at the shell base. The remainder of the bottom edge and the complete top edge were left unrestrained. Symmetry was exploited to model a single panel in each analysis, with symmetry boundary conditions for the adjacent panels. The only load used was the self-weight of the panel. After a few trials, it was determined that a uniform mesh with 10,000 S4R linear rectangular elements would suffice to model each panel. Both linear static analyses (LA) and geometrically nonlinear static analyses (GNA) were performed. The outcomes are presented briefly below.

5.1 INVESTIGATION OF THE *R*/*T* RATIO AND NUMBER OF SUPPORTS

The effect of the r/t ratio are shown in Fig. 5, but are limited to the results for 8 supports due to space restrictions. The r/t ratio was kept below 1500 as excessive deformations and instability phenomena developed in calculation of thinner shells. The results for three different panel heights are presented. The heights were normalised relative to $\sqrt{(rt)}$ to give the dimensionless length ω as in EN 1993-1-6 [12]. The effect of the decrease in thickness is similar regardless of the panel's height. In the radial direction, the decrease in thickness from $r/t = 1000$ to 1500 results in an increase in the deformation amplitudes of approximately 140%. The differences between the LA and GNA analyses are significant only in thinner shells and decrease rapidly in thicker shells. In the meridional direction, the resulting deformation amplitudes are significantly lower and the differences between the structural analyses are negligible, even in the case of the thinnest of shells. Finally, in both the radial and circumferential directions, an increase in the panel height causes higher deformations and thus larger geometric deviations.

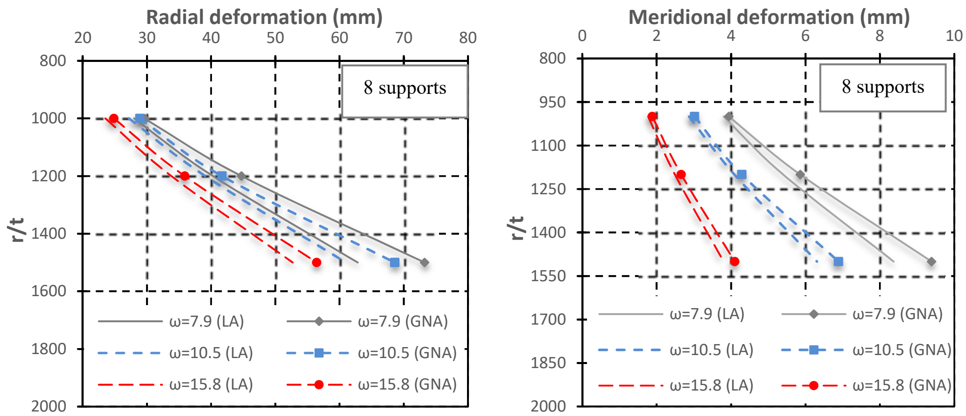

Figure 5: Radial and meridional deformations in the case of 8 supports, varying r/t ratio and panel height ω.

The effect of the number of supports was examined next (Fig. 6). The presented outcomes relate to *r*/*t* = 1500 and three different panel heights. The first successful analysis was conducted for 7 supports and the differences between LA and GNA analyses are significant. Furthermore, the addition of a single support excessively reduced the deformation amplitudes as well as the differences between the structural analyses.

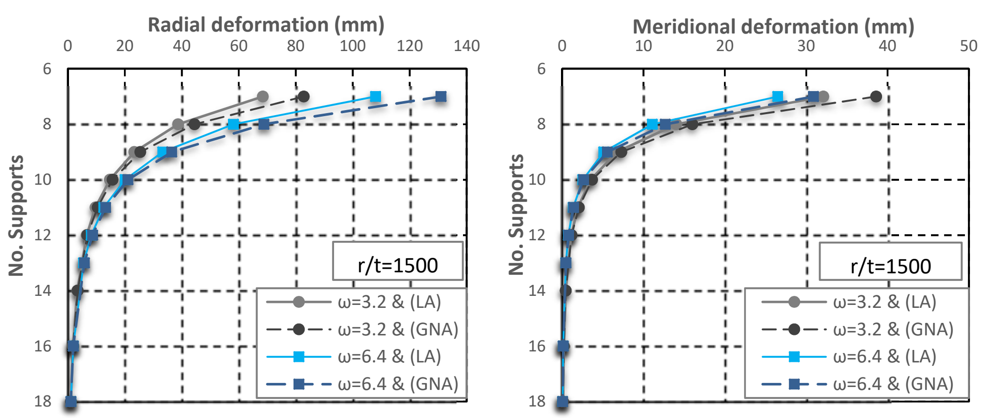

Figure 6: Radial and meridional deformations in the case of r/t ratio = 1500, varying no. of supports and panel height ω.

It should be noted that these effects are well described by semi-membrane treatments of discretely supported shells [14-16] and that the calculated shapes of these silo deformations correspond well with previous descriptions [15].

6. CONCLUSIONS

Several conclusions can be drawn from this study. Two constructed silo shells were measured during an investigation of their acceptability in meeting tolerance requirements. The data from these measurements has been analysed and has revealed a strong correlation between the distortions in the final shell and the method of fabrication. This is an important finding both for tolerance definitions in standards and contracts and for construction techniques.

The pattern of the measured distorted shapes of these constructed shells was efficiently described using Fourier decomposition and showed a clear link between the number of jack supports used and pattern of deformations. Although large geometric deviations were observed, both silos were deemed acceptable according to the tolerance demands of

EN 1993-1-6 but not according to API 650. A following parametric finite element study verified the link between the number of supports and the deformed configuration, and explored the influence of the r/t ratio, the number of supports and the panel height. This study confirmed that the thickness does not significantly affect the deformed shape but does affect the deformation amplitudes. An increase in the panel height also caused larger deformations. More significantly, the number of supports has a strong influence on the radial deformations. The key conclusion is that the number of supports used is critical to meeting out-of-round geometric tolerances during the construction of large shells.

7. REFERENCES

[1] ABAQUS, Abaqus theory manual and user's manual, version 14.2. Pawtucket, Rhode Island, USA, Hibbit, Karlsson and Sorensen Inc, 1998.

[2] Malik, Z., Morton, J. & Ruiz, C. "Ovalization of cylindrical tanks as a result of foundation settlement", *The Journal of Strain Analysis for Engineering Design*, Vol. 12, No. 4, 1977, pp. 339–348.

[3] Kamyab, H. & Palmer, S.C. "Displacements in Oil Storage Tanks Caused by Localized Differential Settlement", *Journal of Mechanical Engineering Science*, Vol. 113, 1989, pp. 60–70.

[4] Kamyab, H. & Palmer, S.C. "Displacements in Oil Storage Tanks Caused by Localized Differential Settlement", *ASME. J. Pressure Vessel Technol,* Vol 113, No. 1, 1991, pp. 71-80.

[5] Hornung, U. and Saal, H. "Stresses in unanchored tank shells due to settlement of the tank foundation", *Proc., Int. Conf. on Carrying Capacity of Steel Shell Structures*, Brno, 1997, pp. 157-163.

[6] Holst, J.M.F.G. and Rotter, J.M. "Nonlinear response and buckling of cylindrical tanks due to foundation settlement", *Proc., International conference on design, inspection and maintenance of cylindrical steel tanks and pipelines*, Prague, Czech Republic, 2003, pp. 29-35.

[7] Holst, J.M.F.G. and Rotter, J.M. "Settlement beneath cylindrical shells in Buckling of Thin Metal Shells", *eds J.G. Teng & J.M. Rotter*, Spon, London, 2004, pp. 129-153.

[8] Holst, J.M.F.G. and Rotter, J.M. "Axially Compressed Cylindrical Shells with Local Settlement", *Thin-Walled Structures*, vol. 43, No. 5, 2005, pp. 811-825.

[9] Teng, J.G., Lin, X., Rotter, J.M. & Ding, X.L. "Analysis of geometric imperfections in full-scale welded steel silos", *Engineering Structures*, Vol. 27, No. 6, 2005, pp. 938–950.

[10] Matlab Release 2015a. Mathworks, Natick, MA, USA; 2013.

[11] Kreyszig, E. "Advanced engineering mathematics", *8th ed. New York, John Wiley & Sons*, New York, 1999.

[12] EN 1993-1-6 "Eurocode 3: Design of steel structures. Part 1-6: general rules-supplementary rules for shell structures". *European Committee for Standardisation,* Brussels, 2007.

[13] American Petroleum Institute, "Welded Steel Tanks for Oil Storage," *API Standard 650*, Washington, DC, 10th ed, 1998.

[14] Calladine, C.R. "Theory of Shell Structures", *Cambridge University Press,* Cambridge, 1983.

[15] Rotter, J.M. "Bending Theory of Shells for Bins and Silos", *Transactions of Mechanical Engineering, Institution of Engineers*, Australia, Vol. ME12, No.3, 1987, pp. 147-159.

[16] Topkaya, C. & Rotter, J.M. "Ring Beam Stiffness Criterion for Column Supported Metal Silos", *Journal of Engineering Mechanics, American Society of Civil Engineers*, Vol. 137, No. 12, 2011, pp. 846-853.

Διερεύνηση των εκτός επιπέδου παραμορφώσεων που αναπτύσσονται κατά τα στάδια κατασκευής κυλινδρικών κελυφών

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Περίληψη

Ο στόχος της παρούσας εργασίας είναι η ανάλυση των παραμορφώσεων που αναπτύσσονται κατά την κατασκευή λεπτότοιχων κυλινδρικών κελυφών εδραζόμενα σε τοπικές ή περιφερειακές στηρίξεις. Το κέλυφος παραμορφώνεται κατά τα πρώτα στάδια της κατασκευής με αποτέλεσμα τα κομμάτια που τοποθετούνται έπειτα να αυξάνουν τις ήδη υπάρχουσες παραμορφώσεις. Αυτό προκαλεί καθυστερήσεις στο διάγραμμα εργασιών και συχνά οι ενέργειες που χρειάζονται για την επιδιόρθωση του προβλήματος αυξάνουν σημαντικά το συνολικό κόστος του έργου. Ανάλογα φαινόμενα έχουν παρατηρηθεί σε αρκετές χώρες σε παγκόσμια κλίμακα.

Στη συγκεκριμένη εργασία, παρουσιάζονται τα αποτελέσματα της αρμονικής ανάλυσης δύο μερικώς κατασκευασμένων κελυφών ώστε να εξεταστεί ο μηχανισμός με τον οποίο αυτά παραμορφωθήκαν κατά την ανέγερσή τους. Στη συνέχεια, το φαινόμενο προσομοιώνεται με τη χρήση του προγράμματος πεπερασμένων στοιχείων, ABAQUS. Έπειτα, η επίδραση των διαφόρων γεωμετρικών παραμέτρων διερευνάτε μέσω μιας παραμετρικής ανάλυσης που διεξάχθηκε. Αξίζει να σημειωθεί ότι, ανεξάρτητα από την ελαστική φύση του φαινομένου, μια ελάχιστη καθίζηση του κελύφους μπορεί να οδηγήσει σε σημαντικές εκτός επιπέδου παραμορφώσεις.