GEOMETRIC DEVIATIONS AND STRUCTURAL BEHAVIOUR OF TANKS AND SILOS

by
Dipl.-Ing. P. Knödel and Dipl.-Ing. F. Wolfmüller
Versuchsanstalt fuer Stahl, Holz und Steine
University of Karlsruhe, FRG

1.   Preface

In design, tanks and silos are considered mostly as ideal and perfect shell structures. In manufacturing, the difficulties of a construction site inevitably cause deviations from the de-signed shape, such as uneveness of the foundations, misalignment of joined sheets, prebuckles due to milling or weld shrinkage and so forth. The designer would not accept a structure with gross imperfections, since he does not want to reduce the opti-mized design-nominal-stresses of a shell structure. The manu-facturer would not accept the designers demand for a perfectly built structure, since he wants to avoid unsuitable high efforts for economical reasons.

A fair solution is to be found as a set of tolerances, where the designers loss in design-nominal-strength is not too big, and where the requirements are easyly met by combining available technology and good practice.

This paper gives a short review on the regulations of present codes, and gives hints on some research work, which is consi-dered with geometrical deviations vs. structural performance.

2.   Admissible Tolerances in Codes

Although pressure vessel codes have much more tradition than tanks and silos, and deal with almost the same problems in limiting geometric deviations /3, 4/, those are not treated in this paper for the sake of its shortness.

2.1 API 620 /1/ and API 650 /2/

These guidelines deal with flat bottom tanks for the storage of products of the petroleum industry. The purpose of tolerances in these standards is to produce a tank of acceptable appearence and to permit a proper function of floating roofs.

Tolerance requirements are ruled as follows:

2.1.1 Plumbness

The maximum out of plumbness of the top of the shell relative to the bottom of the shell shall not exceed 1/200 of the total tank height. The out of plumbness of the shell plates shall not exceed the values specified for mill tolerances according to the relevant codes.

2.1.2 Roundness

Radii measured at 1 foot above the bottom corner weld shall not exceed the tolerances given in the following table:

diameter	0 to 40 feet exclusive	± 0,50 inch
diameter	40 to 150 feet exclusive	± 0,75 inch
diameter	150 to 250 feet exclusive	± 1,00 inch
diameter	250 feet and over	± 1,25 inch

2.1.3 Peaking and Banding

With a horizontal sweep board 36 inches long, peaking, as well as banding, shall not exceed 0,5 inch.

2.1.4 Foundation

The top of a concrete ringwall shall be level within ± 0,125 inch in any 30 feet of the circumference and within ± 0,25 inch in the total circumference measured from the average elevation.

A foundation without ringwalls shall be level within ± 0,125 inch in any 10 feet of circumference and within ± 0,5 inch in the total circumference measured from the average elevation.

2.2 BS 2654 /8/

Like the previous codes, British Standard 2654 is designed for flat bottom storage tanks for products of the petroleum industry. The tolerances are ruled as follows :

2.2.1 Foundation

The difference in level of the surface of the tank foundation

between any two points 10 m apart around the peripherie of the tank shall not be greater than ± 6 mm and the envelope of the peripheral surface levels shall lie within 12 mm above to 12 mm below the design level.

2.2.2   Shell Wall
The internal radius measured horizontally from the centre of the tank at floor level shall not vary from the nominal internal radius by more than the following :
(a) tanks ≤ 12,5 m diameter: ± 13 mm
(b) tanks ≥ 12,5 m diameter: ± 19 mm
(c) tanks ≥ 45,0 m diameter: ± 25 mm.

The overall height of the shell shall not be out of the vertical by more than 1/200.

Local departures from the design:
At horizontal and vertical joints the shell profile should not deviate from its design by more than the following:
(a) plates ≤ 12,5 mm thick: 10 mm
(b) plates ≥ 12,5 mm ≤ 25 mm thick: 8 mm
(c) plates ≥ 25,0 mm thick: 6 mm

Misalignment of the plates in butt welds shall not exceed the following:
(a) vertical joints: 10% of the plate thickness or 1,5 mm for plates ≤ 19 mm thick, and 3 mm for plates > 19 mm thick, whichever is the larger
(b) horizontal joints: 20% of the upper plate thickness or 1,5 mm for plates ≤ 8 mm thick, and 3 mm for plates > 8mm thick, whichever is the larger.

2.2.3   Floating Roofs
The difference in the gap between the shell and the periphery of the roof on completion of erection of the roof shall not exceed ± 13 mm from the nominal gap.

2.3 DIN 4119 /11/
This German standard rules the design and construction of low pressure storage tanks with flat bottom. Allowable tolerances are ruled as follows :

2.3.1 Foundation

The deviations in level shall not exceed 0,1% of the distance between two measuring points, which shall be $\leq$ 5 m, or max. 12 mm.

2.3.2 Tank Bottom

The flat bottom shall not rise from the bearing surface by more than 0,25% of the diameter or max. 10 mm.

2.3.3 Shell Wall

The deviation from the nominal diameter, measured close to the bottom, shall not exceed ± 0,1% or max. ± 40 mm. Deviations of the shell axis shall not exceed 0,5% of the sheet heigth or the total shell height, if the deviation of the nominal diameter is smaller than ± 80 mm. The local out of roundness, measured by a sweep board of 500 mm length shall not exceed 10 mm. The vertical deviation of the tank axis shall not exceed 0,2%.

2.4 DIN 18800 Part 4 /10/

The German draft standard DIN 18800 part 4 regulates buckling of shells. It is the successor of DASt-Ri 013 /9/ and contains many regulations known from the latter, but has been harmonized to the design procedures valid for plates and beams.

It is well understood, that imperfections, i.e. deviations from the perfect geometry of a shell, are the main reason for the reduced bearing capacity of real built shell structures, compared to the high theoretical bearing capacity of an imagined perfect shell.

There is a distinction between the major kinds of possible geometrical deviations:

2.4.1 Initial Radial Imperfections (Prebuckles)

The initial radial imperfections are reducing the bearing capacity of a shell most drastically. Those prebuckles in a ready manufactured shell are to be determined by use of a template of a length $Lm = 4 \cdot \sqrt{(R \cdot t)}$. This length is about the wave length of the critical meridional eigenmode for spheres under external pressure and for cylinders under external pressure or axial compressive forces. For measurements along the circumference of cylinders and cones the length of the template is to be $Lm =$

$2,5 \cdot R/(\sqrt{(R/L)} \cdot \sqrt{\sqrt{(R/T)}})$. Crossing welds, the template is to be Lm $\leq$ 500 mm. The maximum admissible radial deviation is 1% of the length of the template used.

2.4.2   Out of Roundness
The parameter for out of roundness is defined as $U = 2 \cdot (Dmax-Dmin)/(Dmax+Dmin)$, where Dmax and Dmin are the maximal or minimal Diameter respectively, found at the structure. This out of roundness U must not exceed 0,5%.

2.4.3   Excentricity
Undesigned excentricities e perpendicular to compressive membrane forces must hold the minimum of $e \leq 0,2 \cdot t$ and $e \leq 3$ mm (see /14/).

2.4.4   Exceeding of Tolerances
All those tolerances may be exceeded up to 100%, but then the design buckling strength has to be reduced according to a given formula.

2.5   ECCS R 4.6 /12/
For cylinders under axial compression the recommendations of the ECCS ask for limitation of imperfections as follows:

'The amplitudes of the imperfection are measured from a straight rod and a circular template held anywhere between welds, respectively against any meridian and against any parallel circle. The length of the rod and the template is Lr = $4\sqrt{Rt}$, but not greater than 95% of the distance respectively between circular welds and between meridional welds. A rod of length Lr = 25t is to be used across circular welds. If the shell is stringer stiffened, the circumferential template shall not exceed 95% of the distance of the stringers.' /12/

These regulations are very similar to those of DIN 18800 part 4 and DASt-Ri 013 (see previous section), naturally, because the German members of the ECCS draft committee were the same persons to design the rules of the German codes for shell buckling.

The inward amplitude measured against the template must be less than 1% of the templates length to have the full reduction factor α. Up to a depth of 2% the factor is linearly reduced to its

half.

It is remarkably, that the comment of the code does not allow heat treatment to straighten the cylinder walls, 'since it does not improve the load carrying capacity. Rather it will replace shape imperfections by additional residual stresses, thereby simulating too good a quality.' /12/

For liquid filled conical shells the length of the rod to be held against any meridian is to be Lr = 3,6•√(Rt/cosß). The largest measures inward amplitude must not exceed 2% of Lr.

3.   Research on Geometric Deviations

Of course the following overview can not handle the research work on geometric deviations of tank structures completely. It merely gives light to some special aspects, onto which research is focussed.

3.1 Effects on Strength

Early works on the effects of geometric deviations on the strength of tubes are the ones of Dr. Schmidt /21, 22/, which have been used for the German pressure vessel code /3/. In the cited papers ring sections are considered, which have a roof-shaped outward imperfection, an oval imperfection of the form $w = w_o•\cos(2\emptyset)$, or a flat indentation. For these types of imperfection formulae are derived, which allow for the calculation of the circumferential bending moment according to a given out of roundness.

The maximum stresses due to a axisymmetric indentation of the geriatrix, as could result of a circumferential weld shrinkage, were determined by means of a FEM analysis in /20/. It was found, that the additional meridional bending stresses are rather high, so that they must be observed with fatigue-loaded shells, even if the demands for the tolerances of a stability code /9/ are met.

3.2 Effects on Stability

Bornscheuer investigated a damage due to geometrical imperfections caused by weld shrinkage in 1957 /6/, and this work has

been continued by him, his co-workers, and his successor on the chair of building mechanics, University of Stuttgart /7/.

Jürcke, Krätzig and Wittek /13/ used a FE procedure to compare the regulations of the DASt-Ri 013 /9/ to numerically determined bifurcation loads of axisymmetric imperfect structures. They found, that inward bulges reduce the buckling load with increasing depth, whereas under certain circumstances outward bulges can act like ring-stiffeners.

Bodarski, Hotala and Pasternak /5/ surveyed 6 steel silos and found radial deflections up to 5 times the respective wall thickness. They give an estimate on the influence of the imperfection depth on the buckling strength.

In a recent paper /14/ Knödel and Maierhöfer report on parameter studies on axially loaded cylinders with edge moments. Since a misalignment of two adjacent strakes causes edge moments in the respective shell parts, their suggested formula can be used to estimate the residual buckling strength due to this type of geometrical deviations. Further information on the state-of-the-art in silo research is given in /19/. Numerical and experimental work on the stability of silos is reported in /15/, the publication of numerical parameter studies with imperfect silos is in preparation.

4. Damages

It has been heard of many damages in tanks and silos, but naturally, few of them have been published in detail (compare /17, 18/). Typical types of damages are local buckling of the shell wall due to unevenness of the support, buckling of the upper part due to out of roundness of the bin when mounting the roof, local damage of the shell due to faulty design of the ends of stringers, and so on. A paper with case studies of such damages is in preparation.

However, trouble may not only occur with the shell itself, but with structural parts, which seem to be standard steel construction. A damage of a 64 m diameter tank is described in /16/, where the roof beams failed during erection due to both, imper-

fections of the beams and shrinkage of the roof sheeting due to a drop of temperature.

5.   Conclusions

The summary of the requirements of the selected codes shows, that all those codes represent about the same technological level. One might have the impression, however, that those regulations result from empirical thumb rules rather than from a deep understanding of the quantity of the additional strains, caused by certain geometrical deviations. This need not be disadvantageous, since almost one century of experience in building pressure vessels, tanks and silos prooved, that the chosen limitations in the codes ensure a proper level of quality.

This system of quality assurance does not any longer seem to fit to the 'modern' steel construction codes with a system of partial safety factors and propabilistic concepts of structural safety. It only seems to be adequate, to have some more research focussed to numerical studies on the structural behaviour of certain types of geometric deviations. Thus, in international cooperation, the regulations in the present codes could be altered to a set of tolerances with known relations to the respective bearing capacity of tank and silo structures.

6.   References

/1/   API 620 Recommended Rules for Design and Construction of Large, Welded, Low-Pressure Storage Tanks. American Petroleum Institute, 7th edition, September 1982.

/2/   API 650 Welded Steel Tanks for Oil Storage. American Petroleum Institute, 7th edition, November 1980.

/3/   Arbeitsgemeinschaft Druckbehälter: AD-Merkblatt HP1 Dimensioning and Design; Construction and Testing of pressure vessels; July 1989. (in German)

/4/   Arbeitskreis Formabweichungen des VdTÜV-FA Berechnung: VdTÜV-Guideline Peaking, Banding and wavy out of Roundnesses; draft September 1987. (in German)

/5/   Bodarski, Z., Hotala, E., Pasternak, H.: On estimating the bearing capacity of metal silos. Bauingenieur 60 (1985) pp 49-52. (in German)

/6/   Bornscheuer, F.W.: Buckling phenomena caused by residual stresses due to welding. Schweissen und Schneiden 9 (1957), pp 492-494. (in German)

/7/   Bornscheuer, F.W., Häfner, L., Ramm, E.: On the stability of a circular cylinder with a circumferencial weld under axial load. Stahlbau 52 (1983), H. 10, pp 313-318. (in German)

/8/   British Standards Institution: BS 2654:1989 - Vertical steel welded storage tanks with butt-welded shell for the petroleum industry.

/9/   German Board for Steel Construction DASt-Guideline 013: Design against Buckling of Shells; Juli 1980. (in German)

/10/   German Standard DIN 18800 Part 4 Steel Structures; Stability; Buckling of Shells; draft August 1988. (in German)

/11/   German Standard DIN 4119 Part 1 and 2 Above Ground Cylindrical Flat Bottom-Tanks, constructed of Metallic Materials; June 1979. (in German)

/12/   European Convention for Constructional Steelwork: European Recommendations for Steel Construction R 4.6, Buckling of Shells, 1984.

/13/   Jürcke, R.K., Krätzig, W.B., Wittek, U.: Circular cylindrical shells with bulge-shaped imperfections. Stahlbau 52 (1983), H. 8, pp 241-244. (in German)

/14/   Knödel, P., Maierhöfer, D.: On the Stability of Cylindrical Shells Subjected to Axial Compressive Loads and Edge Moments. Stahlbau 58 (1989), H. 3, pp 81-86. (in German)

/15/   Knödel, P., Schulz, U. Buckling of Silo Bins loaded by Granular Solids. pp 287-302 in Eibl, J. (ed.) Proc., 2nd Int. Conf. "Silos - Forschung und Praxis, Tagung '88". SFB 219, University of Karlsruhe, 10.-11. October 1988.

/16/   Lohse, W., Meister, J.: Conclusions from a damage - on the calculation of truss-rib roofs of tanks. Schweissen und Schneiden 30 (1978), H. 9, pp 353-357. (in German)

/17/   Mang, F., Bremer, K.: Large-Diameter Pipelines and Vessels. Chapter 32 in Stahlbauhandbuch, Vol. 2, Stahlbau-Verlagsgesellschaft mbH, Cologne, 1985. (in German)

/18/   Mang, F., Wolfmüller, F.: Recent Problems in Calculation and Strength with Building Vessels, Apparatuses and Pipelines. in Selected Chapters of Building Vessels, Apparatuses and Pipelines. Haus der Technik e.V., Essen, March 1989. (in German)

/19/   Mang, F., Knödel, P., Wolfmüller, F.: New Developments
         in the Design of Metal Single- and Multi-Chamber Si-
         los. Proc., 10 Years of Progress in Shell and Spatial
         Structures, 30 Anniversary of IASS, Vol. 1, Madrid,
         11-15 September 1989.

/20/   Simon, G.: Stressing of a circular cylinder incorpora-
         ting a circumferential weld, in axial loading. Stahl-
         bau 56 (1987), H. 11, pp 343-347. (in German)

/21/   Schmidt, K.: On the calculation of stresses in out-of-
         round pipes subjected to internal pressure. VDI-Z. 98
         (1956) Nr. 4, pp 121-164. (in German)

/22/   Schmidt, K.: Stresses in out-of-round pressure ves-
         sels. VDI-Z. 102 (1960) Nr. 1, pp 11-15. (in German)