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Citation for published version (APA):

Maraveas, C., Jármai, K. (Ed.), & Farkas, J. (Ed.) (2013). Structural Appraisal of Two Steel Tanks Filled at Low Liquid Level. In K. Jármai, & J. Farkas (Eds.), *Design, Fabrication and Economy of Metal Structures, International Conference Proceedings 2013* (pp. 211-216). Springer Nature.

Published in:

Design, Fabrication and Economy of Metal Structures, International Conference Proceedings 2013

Citing this paper

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Structural Appraisal of Two Steel Tanks Filled at Low Liquid Level

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Abstract. The object of this paper is to evaluate the structural adequacy of two existing large diameter steel tanks filled at low liquid levels by application of current design specifications. Emphasis is given on buckling of the circumferential shell and phenomena related to overall stability. Calculations according to the American standard API 650, which provides analytical expressions for determining overturning and sliding resistance as well as a design procedure for stiffening the shell against wind action, are presented. Simulation of the tanks via the finite element method, for obtaining the necessary shell stresses, was performed as required by the European standard EN1993-1-6. Based on the results, overall stability was checked and shell buckling was evaluated according to the “stress design” concept described in the aforementioned code. Differences in the results between the two standards are discussed and comments regarding their safety are made.

Keywords: steel tanks, low liquid level, shell buckling, overturning stability, sliding resistance.

1 Introduction

The use of thin-walled large diameter steel tanks used for liquid storage has seen a steep rise during the past decades. Current design philosophy focuses on the prevention of structural failures associated with tanks filled at high levels (plastification of the shell due to hydrostatic pressure, failures resulting from seismic loading), even though other limit states, such as buckling of the shell, are considered. However, when tanks are required to operate at low levels of the contained liquid for prolonged periods, the effect of other actions, such as wind, is expected to become more profound and dictate the failure pattern. This paper attempts to appraise the structural adequacy of two existing oil storage tanks filled at low level by applying the provisions of current design standards.

2 Description of Tanks

The two thin-walled, flat bottom steel tanks (T-776 and T-761) located in the oil refinery of Motor Oil Hellas S.A. (Korinthos, Greece), are shown in Fig.1. Both are cylindrical, self-supported and have variable wall thickness. Tank T-776 has a conical roof attached to its shell. Ring stiffeners have been placed at distinct locations of their circumference. The geometrical data of the tanks are presented in Table 1 and detailed information related to their shell is given in Table 2.

Fig. 1. Photographs of tank T-776 (left picture) and tank T-761 (right picture)

Table 1. Geometry of tanks T-776 and T-761

Tank ID	Shell	Roof	Liquid	Inside	Location ¹ of 1 st	Location ¹ of 2 nd
	Height (m)	Height (m)	Level (m)	Diameter (m)	Wind Girder (m)	Wind Girder (m)
T-776	20.032	3.911	1.0	46.939	14.860	-
T-761	19.500	No roof	0.5	88.430	15.350	18.400

1. Refers to the height measured from the bottom of the tank.

Table 2. Information regarding the shell courses of tanks T-776 and T-761

Course No. ¹	Course		Course		Minimum specified	
	Thickness (mm)		Width (mm)		Yield stress (MPa)	
	Tank T-776	Tank T-761	Tank T-776	Tank T-761	Tank T-776	Tank T-761
1	22.25	38.60	2438	2222	345	345
2	18.93	37.18	2438	2222	345	345
3	16.24	28.20	2438	2222	345	345
4	13.57	24.59	2438	2222	345	345
5	10.9	19.96	2438	2222	345	345
6	8.22	15.60	1940	2222	345	345
7	8.00	11.20	1940	2222	275	345
8	8.00	9.50	1940	2222	275	245
9-top	8.00	9.50	1940	1724	275	245

1. Courses are numbered from bottom to top (i.e. No.1 refers to the bottom shell course etc.).

3 Wind Design of the Shell According to API 650

Buckling of the tank's shell per API 650 (2007) is considered indirectly via a design approach, according to which, the circumference of the tank is stiffened with wind girders (stiffening rings). Their location and number depends on the height of the "transformed" shell (calculated according to thickness variation) and a specified height H_1 that depends on wind velocity and tank geometry. API 650 (2007) also includes a mathematical formula for the maximum longitudinal compressive stress σ_c resulting from seismic motion, which should not exceed a resistance stress F_c . The latter is a function of the tank geometry and materials.

Relevant calculations referring to the tanks are summarized in Table 3. The design wind speed was selected equal to 190 km/h. The contained liquid was assumed to have a specific gravity of 0.7.

Table 3. Shell stability evaluation for tanks T-776 and T-761 per API 650

Tank ID	Height H_1 (m)	Height of transformed shell (m)	Height ¹ of the lower unstiffened part (m)	Height ¹ of the upper unstiffened part (m)	Stress σ_c (MPa)	Stress F_c (MPa)
T-776	5.330	10.290	5.200	5.090	2.2	22.2
T-761	3.167	6.901	2.820	2.981	1.2	18.9

1. Refers to the height of "transformed" shell.

4 Shell Buckling Evaluation per EN1993-1-6

The design of thin-walled steel tanks is also covered in the European standard EN1993-4-2 (2007), which refers to EN1993-1-6 (2007) for assessing buckling of axisymmetric shell structures. The latter proposes several design methodologies, but the "stress design" concept (which involves comparison of shell stresses obtained from linear elastic analysis with design resistances calculated from analytical expressions) was selected for buckling evaluation of tanks T-776 and T-761.

The finite element method (FEM) was employed to model the two tanks. STAAD.Pro V8i (2007) software was selected to carry out the necessary linear elastic analyses. The shell, bottom and roof plates were simulated by plate elements, which account for membrane action and bending, a requirement set by EN1993-1-6 (2007). Beam elements were used for simulating the structural members of the tanks. Linear elastic supports were assumed for their foundation. The FE mesh was selected to account for the change in shell thickness and the location of stiffeners. Modelling of the contained fluid via solid elements (Cho, Song and Lee 2001; Greiner and Kettler 2005; Liu 1981; Maraveas 2011) for simulating its effect on the tank during seismic motion was not adopted here. This is reasonable, because in tanks filled at low levels, the liquid moves out-of-phase with respect to the tank shell (convective mode). The created FE models are shown in Fig. 2.

Fig. 2. FEM modelling of tank T-776 (left side) and tank T-761 (right side)

The loading actions considered in the analyses were according to: i) EN1991-1-1 (2002) for self-weight, contained liquid weight and live load ii) EN1991-1-4 (2005) for wind loading iii) EN1991-1-5 (2004) for temperature loads iv) EN1998-1 (2005) and EN1998-4 (2007) for seismic loading. EN1990 (2002) was used to combine the above actions. The horizontal and vertical linear elastic response spectrums per EN1998-1 (2005) were used in conjunction with the following parameters: i) behaviour factor $q=1$ ii) ground type C iii) 5% damping (EN1998-4 2007) iv) importance factor 1.40 v) peak ground acceleration 0.24g (Korinthos, Greece). The lateral force method was applied, with the hydrodynamic pressure being calculated according to EN1998-4 (2007).

Table 4. Utilization ratio for shell buckling of tanks T-776 and T-761 per EN1993-1-6

Course No. ¹	Fabrication Quality Class					
	Class A		Class B		Class C	
	Tank T-776	Tank T-761	Tank T-776	Tank T-761	Tank T-776	Tank T-761
1	2.75	0.91	3.32	1.14	4.66	1.75
2	1.50	2.03	1.86	2.43	2.69	3.38
3	2.00	1.29	2.54	1.55	3.78	2.16
4	2.17	1.42	2.90	1.71	4.51	2.41
5	2.45	1.47	3.52	1.74	5.87	2.48
6	3.08	1.65	4.90	2.13	8.83	3.22
7	1.83	0.99	2.11	1.74	3.74	3.11
8	2.56	1.67	3.68	2.42	6.14	1.77
9-top	1.02	0.81	1.17	1.02	1.52	1.50

1. Courses are numbered from bottom to top (i.e. No.1 refers to the bottom shell course etc.).

Results pertaining to shell buckling evaluation are shown in Table 4. The utilization ratio for the critical load combination is given at the middle of each course. In all cases, wind action induced the most severe stress resultants in the shell. The buckling resistance was evaluated according to the procedure described in Annex D of EN1993-1-6 (2007) for tanks with stepwise variable wall thickness. Stress interaction

was accounted for as mandated by EN1993-1-6 (2007). Results for all fabrication quality classes (which quantify the effect of imperfections on buckling resistance) specified in EN1993-1-6 (2007) are shown for comparison purposes.

5 Overall Equilibrium of Tanks

Attention was also given to evaluating the overturning stability and sliding resistance of the studied tanks. API 650 (2007) provides analytical relationships for verifying the overall equilibrium of tanks subjected to wind action and seismic excitation. Based on these, the safety factors against overturning and sliding for tanks T-776 and T-761 were calculated and are presented in Table 5. The assumed coefficient of friction was 0.4. Furthermore, their overall equilibrium was checked for wind loading per EN1991-1-4 (2005) and seismic action per EN1998-1 (2005) and EN1998-4 (2007). Relevant safety factors are also shown in Table 5.

Table 5. Overall stability of tanks T-776 and T-761

Factor of Safety	Wind Action				Earthquake loading			
	API 650		EN1991-1-4		API 650		EN1998-1	
	Tank T- 776	Tank T- 761	Tank T- 776	Tank T- 761	Tank T- 776	Tank T- 761	Tank T- 776	Tank T- 761
Sliding	7.3	9.2	14.1	18.9	2.1	2.1	1.6	1.3
Overturning	1.7	31.7	63.1	164.5	1.7	5.6	7.4	14.2

6 Conclusion

The provisions of API 650 (2007) are met for both tanks. On the contrary, the buckling requirements per EN1993-1-6 (2007) are not fulfilled for either tank. Results show that shell resistance is exceeded in a major way (more than three times) by the design stresses, especially for the thinner courses close to the top. Stiffening of the shell is necessary for satisfying the requirements of this code. This contradiction raises serious doubts regarding the safety of the tanks, suggesting that current design codes might not be sufficient for evaluating shell buckling of thin-walled tanks. Further improvements on their provisions should be made in order for a safe and efficient design to be achieved. Moreover, operation of the tanks for the specified low liquid levels is not critical for their overall stability. The large discrepancies observed in the overturning stability safety factors related to wind action result from the difference in application of the load and a relevant check mandated by API 650 (2007) that accounts for stability of the tank without its contents.

Acknowledgements. The authors gratefully acknowledge the contribution of Motor Oil Hellas, Korinthos Refineries S.A. and the supervisor of the project Mrs. Sofia Dimitrakaki.

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