Mühendis ve Makina
cilt 63, sayı 708, s. 540-559, 2022
Araştırma Makalesi

Engineer and Machinery
vol. 63, no. 708, p. 540-559, 2022
Research Article

DOI: 10.46399/muhendismakina.1108194

Elasto-Plastic Deformation of a Liquid Ammonia Storage Tank

Göksel Saraçoğlu[1]

ABSTRACT

This paper presents the elasto-plastic deformation of the inner bottom plate of a 10,000 tonnes capacity double wall liquid ammonia storage tank used in a chemical fertilizer plant. It has been determined that the problem encountered in the bottom plate of the tank where the raw material is stocked at -33°C is caused by the rapid cooling of the tank after the internal maintenance. Mechanical tests performed on the sample cut from the bottom plate showed that the plastic deformation occurred at a rate of 1.94%, but the toughness was at a level that did not require a change. Therefore, it is foreseen that the use of the bottom plate can be continued by complying with the 1°C/hour heating and cooling rule in accordance with the relevant standard API-620.

Keywords: Elasto-plastic deformation, liquid ammonia tank, the Bauschinger effect, low pressure tank, rapid heating and cooling

Bir Sıvı Amonyak Depolama Tankının Elasto-Plastik Deformasyonu

ÖZ

Bu çalışma, bir kimyasal gübre fabrikasında kullanılan 10.000 ton kapasiteli çift cidarlı sıvı amonyak depolama tankının iç taban sacının elasto-plastik deformasyonunu sunmaktadır. Hammaddenin -33°C'de stoklandığı tankın taban sacında karşılaşılan problemin, tankın bir önceki iç bakım sonrası hızlı soğumaya maruz bırakılmasından kaynaklandığı tespit edilmiştir. Taban sacından kesilen numune üzerinde yapılan mekanik testler, plastik deformasyonun %1,94 oranında gerçekleştiğini ancak tokluğun değişiklik gerektirmeyen bir seviyede olduğunu göstermiştir. Bu nedenle ilgili standart API-620'nın belirttiği 1°C/saat ısıtma ve soğutma kuralına uyularak mevcut taban sacının kullanımına devam edilebileceği öngörülmüştür.

Anahtar Kelimeler: Elasto-plastik deformasyon, amonyak tankı, Bauschinger etkisi, düşük basınçlı tank, hızlı ısıtma ve soğutma

Geliş/Received : 24.04.2022
Kabul/Accepted : 02.07.2022

[1] İskenderun Teknik Üniversitesi Havacılık ve Uzay Bilimleri Fakültesi Uçak Bakım ve Onarım Bölümü, İskenderun Hatay
goksel.saracoglu@iste.edu.tr, ORCID: 0000-0002-0211-0540

1. INTRODUCTION

Liquid ammonia is used as an input in many production facilities, especially in chemical fertilizer production facilities. The storage of the product, which performs the liquid-gas conversion at -33°C under normal conditions, differs from hydrocarbon storage in terms of low temperature, pressure and product emission harms to health, safety and the environment. Therefore, some Standards have been established specifically for the material, manufacture and operation of the storage tank [1-3].

The tank is insulated to prevent intense evaporation due to heat transfer in the liquid ammonia stored in the tank at -33 °C. Some tanks have a single wall and insulation is formed on the outer surface of the wall. As in the tank considered in this study, some tanks are double-walled and the insulation is between two walls (shells). In the tank, ammonia vapor is formed on the liquid ammonia and this vapor is sucked from the tank and sent to the cooling cycle facility and condensed again and injected into the roof of the tank. The condensed product injected inside provides heat withdrawal from the internal environment of the tank.

Another issue that will threaten low temperature and cryogenic tanks is the frequency of in-tank inspections performed on hydrocarbon tanks. No matter how suitable the materials used are, more frequent internal inspections of the tank can lead to stress corrosion cracking. The European Fertilizer Manufacturers Association (EFMA) stated the insidious danger in its publications and emphasized that internal controls should be carried out in a period to be determined in accordance with the risk assessment of tanks [4].

It can be stated that the thermal cycle will be more dangerous than being constantly at low temperature. Internal control of the tank means the incorporation of atmospheric oxygen into the tank. The lower flammable limit of oxygen in the tank for ammonia is 16%. In addition to stress corrosion cracking, not using inert gas (e.g., nitrogen) in the charging and discharging of the tank also brings with it the negativities that may result in the explosion of the tank [5].

The negative situation to be experienced in the chemical process industry brings with it difficult questions such as where the product will be unloaded from the tank, how it will be evacuated, what measures should be taken to prevent the production from being interrupted, and with what budget the repair of the tank will be made. There have been many disasters and undesirable situations caused by not paying attention to the specified aspects of ammonia storage tanks [6-10].

In the literature, it has been determined that the plastic deformation of the storage tank operating at low temperature due to thermal cycling or rapid filling has not been adequately examined. A method is presented for the analysis of the base plates in cylindrical liquid-storage tanks that are uplifted under the overturning influence of the hydrodynamic wall pressures induced by earthquakes [11]. It is foreseen that the study can fill the gap in this field.

This paper presents the elasto-plastic deformation of the inner bottom plate of a 10,000 tonnes capacity double wall liquid ammonia storage tank used in a chemical fertilizer plant. It has been determined that the problem encountered in the bottom plate of the tank where the raw material is storoaged at -33°C is caused by the rapid cooling of the tank after the internal maintenance. Mechanical tests was performed on the sample cut from the bottom plate and the toughness was measured at a level that did not require a change. Therefore, it is foreseen that the use of the bottom plate can be continued by complying with the 1°C/hour heating and cooling rule in accordance with the relevant standard API-620.

2. CONSTRUCTION AND HISTORY OF THE TANK UNDER INVESTIGATION

The liquid ammonia storage tank investigated in this paper is a double-walled and bot-

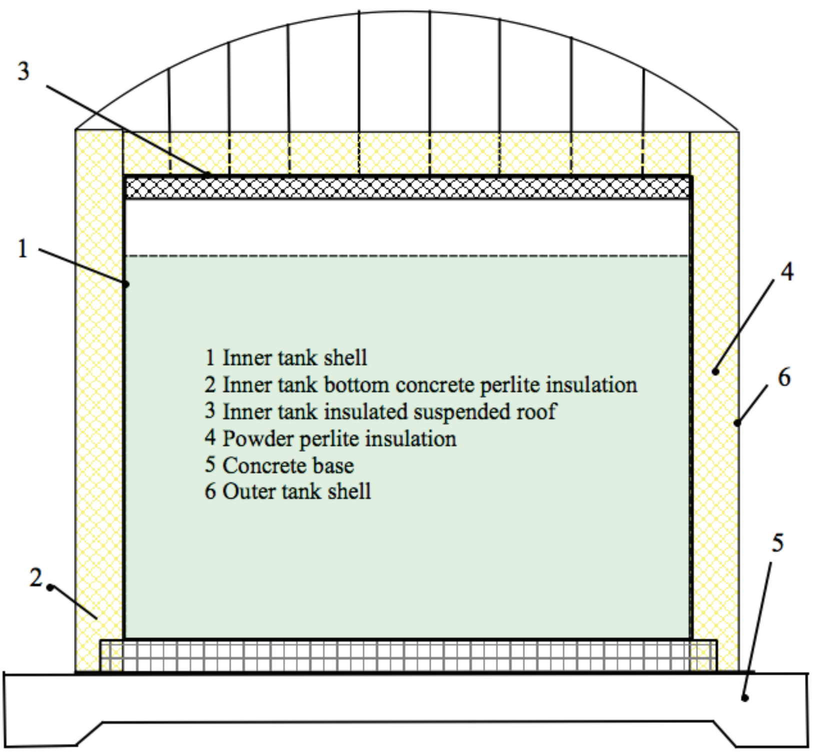


Figure 1. Schematic View Of Double-Wall Low Pressure Ammonia Tank

tomed tank with a 10,000 tonnes capacity, constructed according to API Standard 620 and 650 [1, 12] and in which anhydrous liquid ammonia at -33°C is stored (Figure 1). Perlite-based insulation materials are used to maintain the temperature of the product between the two tanks.

In this construction type, both the inner and outer tanks are capable of containing the refrigerated liquid stored independently. The inner tank contains the refrigerated liquid under normal operating conditions. The roof is supported by the outer tank. The outer tank is capable of containing both the refrigerated liquid and the vapor resulting from product leakage and is located between 1-2 meters from the inner tank. In such tanks, secondary containment in the form of dyke wall is not required. The double containment tank design, also known as the "cup-in-tank" (double integrity) design is widely adopted for ammonia storage tanks. The inner cup of the tank is separated from the outside tank by a suspended deck resting on the top of the inner cup.

The present day tanks are constructed on elevated concrete foundations to avoid the problem of ice formation and propagation in the soil below [13, 14].

The bottom plate in question is made of pressure vessel steel (ASTM A516 Gr 60) with a thickness of 6 mm and a minimum operating temperature of -40°C. The rigidity of the tank has been increased in accordance with the API Standard 650 by using 8 mm thick plates (annular plate) of the same material in the parts of the bottom plate area close to the wall. The first shell plates of the inner and outer tanks are constraint by wind beams which is anchored to the ground and press the shell plate with the spring force (Figure 2).

A pressure vessel steel (ASTM A 516 Gr 70) with a minimum operating temperature of -40°C is used in the shell of the inner tank. Shell plates thins out in accordance with the API Standard 650 when the upper level is reached.

The disadvantages that may threaten the structure in such tanks operated under cryogenic conditions can be listed as follows [4]:

a) While the tank is in operation, the presence of oxygen to enter will cause stress corrosion cracking,

b) The deformation that will occur in the face of sudden heating and cooling of the tank exceeds the elastic limit.

It is recommended to sweep the ammonia tanks with a neutral gas (nitrogen gas) in order to prevent the presence of oxygen of air in the ammonia tanks and therefore the stress corrosion cracking, as well as to prevent the risk of explosion and the mixing of ammonia with air at dangerous rates. When the service and maintenance history of the ammonia tank is examined, it has been determined that there is no record of whether neutral gas was used or not when it was first commissioned. Nitrogen gas was also not

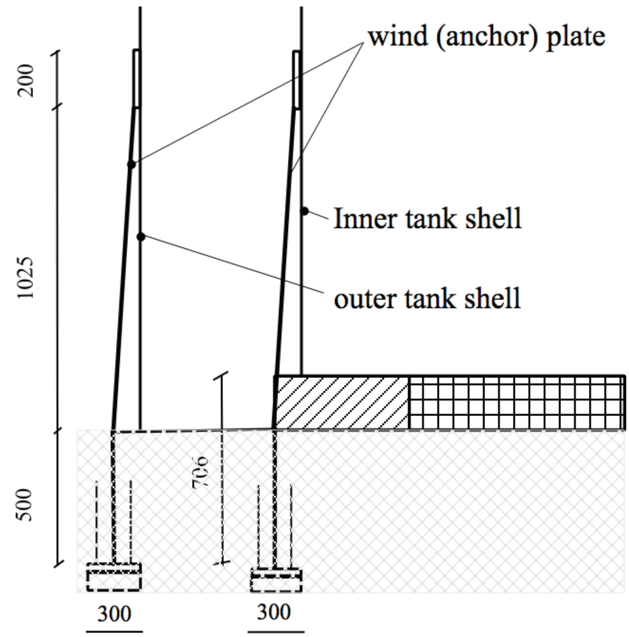


Figure 2. The Schematic View of Double Wall Anchorage System

used in the first inspection, but in the second inspection, it was used in the process of scavenging the air or ammonia gas.

The second criterion that threatens the tank is the permanent elongation of the tank material above its yield strength. This issue is not related only to the use of steel materials of appropriate structure, but also to reducing the tank to the regime temperature or bringing it to ambient temperature at a certain speed. API Standard 620 and 653 Codes recommend heating or cooling tanks at 1°C/h [15].

The first internal control and maintenance of the tank was carried out approximately 18 years after its commissioning. In this control, no negative situation was encountered inside the tank. In accordance with the Occupational Health and Safety Law, a Risk Based Analysis (RBI) study was carried out under the advice and assessment drawn by the European Fertilizer Manufacturers Association (EFMA), and it was decided to carry out internal inspections for 15-year periods [4]. As a result of these studies, the second internal inspection of the tank was planned and carried out 33 years after its commissioning.

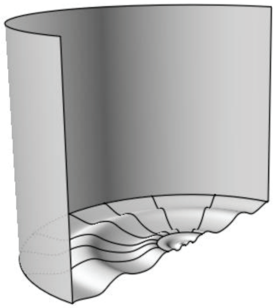
In the second inspection, unlike the first, fluctuations up to 240 mm in height were detected in the bottom plate of the inner tank with a diameter of 29,650 mm (Figure 3 and 4a).

Figure 3. Plastic Deformation Of The Bottom Plate a) Measuring The Fluctuation in the Tank Bottom Plate, b) Appearance of Deformation From The Location Close to The Shell

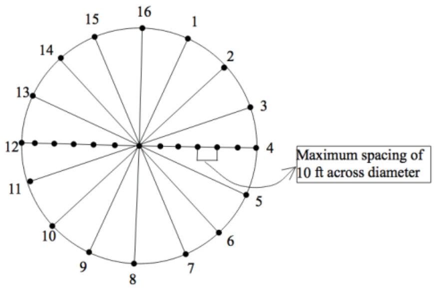
Considering the API Standard 653, the values in Table 1 were encountered when the heights of the wavy form of bottom plate were measured within a systematic as seen in Figure 4b.

First of all, the amount of plastic deformation was evaluated of the bottom plate of the inner tank according to Annex B-2 of the API-653 Code [15]. Accordingly, the maximum collapse value at the bottom of the tank was measured as 28 mm, the highest bulge value as 265 mm, and it was stated that it exceeded the limit value of 62 mm calculated according to the relevant Code.

In this case, a preliminary report was issued that the tank bottom plate cannot be used and the tank needs to undergo a rehabilitation.



(a)



(b)

Figure 4. Measurement procedure of bottom plate collapses and bulges according to API 653 Std. (a) schematic view of bottom plate for measurement, (b) The Standard specification for measurement [15]

Table 1. Bottom Plate Collapse Depth and Bulge Height Values (all collapses and the bulges above 50 mm are colored)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
14812	0	9	11	4	14	8	16	15	18	0	8	3	2	-3	-1	-11
13812	51	63	77	-1	104	119	105	141	130	168	135	136	60	132	127	56
12812	34	56	147	-15	163	174	155	198	189	214	240	210	171	214	213	122
11812	-6	2	136	14	87	110	170	104	202	124	164	246	246	265	229	171
10812	86	66	65	60	2	28	51	30	92	32	79	190	190	198	196	172
9812	151	149	1	0	-5	0	2	9	2	-8	7	63	83	83	216	183
8812	75	41	-7	15	27	18	0	1	8	8	3	14	20	23	177	210
7812	2	-11	-10	27	29	15	22	5	-2	17	12	-6	-9	13	35	108
6812	-6	-7	-8	-9	-4	24	11	-5	-9	6	9	6	-9	32	-8	-7
5812	-6	-14	-13	-4	-3	24	6	0	-6	13	0	26	-6	21	12	-18
4812	5	-28	-2	-6	17	-1	10	22	-4	33	22	2	21	16	23	-5
3812	5	-25	1	-13	4	-14	-4	5	-1	20	27	-15	8	6	4	0
2812	-15	-20	-13	-8	1	-7	-1	-10	11	-1	6	-5	28	32	25	15
1812	-13	-16	1	10	8	17	8	9	21	14	6	26	21	9	11	9
812	-4	-5	-6	-5	-3	-3	-3	-6	6	10	8	8	4	1	-10	-3
0	-3	-4	-10	-1	-10	-1	-7	2	6	-2	6	-1	-2	2	0	-2

Figure 5. Bending of the First Shell a) Schematic View of the Deformation, b) Shell Verticality Measurement

Another important result obtained from the field studies was that the inner tank (first) shell lost its verticality by bending (Figure 5). In the relevant (preliminary) report, it was reported that dishing occurred at the lowest level of 20 mm and the highest level of 38 mm during the verticality control along the tank perimeter, and it was stated that it was not suitable because it exceeded the limit level of 13 mm according to the API Standard 650 [12].

3. TAKING THE PRODUCT INTO THE EMPTY TANK

The bottom plate cannot compensate itself after the product is taken into the tank or product is withdrawn from the tank rapidly, and it undergoes plastic deformation by exceeding the elastic limits. During the instant product intake into the tank, the shell, which is approximately three times larger than the bottom plate in surface, cannot cool sufficiently. However, in this situation, the bottom plate will be wet by the product and needs to shrink. The shell of the tank will resist this need and the bottom plate undergoes elasto-plastic deformation by exceeding the yield stress. The biggest issue affecting the structural strength of low temperature and cryogenic tanks is the speed of product intake.

The inner bottom diameter of the anhydrous ammonia tank is 29,634 mm. This length is the distance (diameter) between the inner surfaces of the first shell. In the part of this area adjacent to the inner shell, there is an 8 mm thick annular plate around the perimeter. Its width is 662 mm from the inner face of the first shell. The diameter of the 6 mm thick base is 28,310 mm (Figure 6).

The technical specification of ASTM A516-60, which is the material of the bottom plate, is presented in Table 2.

Table 2. Bottom Plate (ASTM A516-60) Material Properties [16]

Features	Value	Unit
Tensile strength	415	MPa
Yield strength	220	MPa
Allowable stress (-33°C)	118	MPa
Thermal expansion (α)	$12.3.10^{-6}$	1/°C
Modulus of elasticity (E)	200	GPa

Consider a strip from the bottom plate of the inner tank which has a diameter length but 1 mm width. Since the inner tank bottom plate is 6 mm thick in the middle and 8 mm thick at annular region, this strip will also have the same geometric feature. The cross-sectional area of this strip will be A_1=6 mm^2 between the annular plate and A_2=8 mm^2 at annular plate. Assume that the product is taken at low speed when all the internal surface of the tank is at about 30°C in the empty condition. After being put into service, this temperature will decrease to -33°C, creating a temperature difference of 63°C. In such a case, the amount of contraction corresponding to this temperature difference would be 23 mm according to Eq. 1.

$$\delta = \alpha(\Delta T)L \tag{1}$$

The (common) force to restore this thermal contraction will be 0.0244 P as a result of Eq. 2. The lengths of the (each) 8 mm thick part (L_1) and the length (L_2) of 6 mm thick part of the strip are 668 mm and 28310 mm, respectively.

$$\delta = \frac{PL_1}{A_1E} + \frac{PL_2}{A_2E} + \frac{PL_1}{A_1E} \tag{2}$$

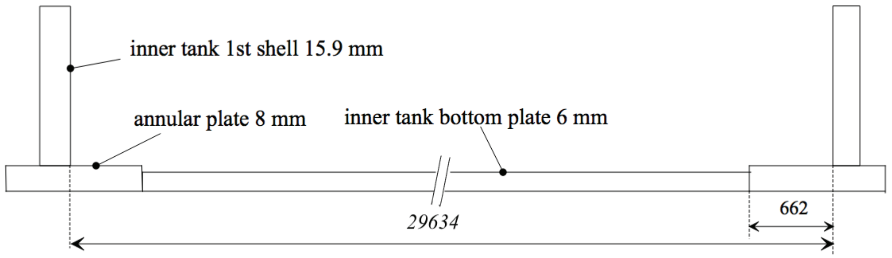


Figure 6. The Schematic Section of Inner Tank

This imaginary strip will not be contracted due to the restraint of the first shell, despite the temperature difference of 63°C. So, Eq. 1 and 2 will be equal to each other. In this case, the force P will be 943 N. The principal stress that will occur in strip sections of 6 and 8 mm thickness will be 157 MPa and 118 MPa, respectively.

When it was desired to verify the obtained values with the non-linear analysis of finite elements method, the close results were obtained as seen in Figure 7 if singularity values are filtered.

As a result of this calculation, it is seen that the stresses occurring in the bottom and the annular plate are different. These stresses are the maximum principal stresses occurring at the entire circumference of the tank. These stress values are emerging when the product-intake begins and only the bottom is wet by product and does not rise too

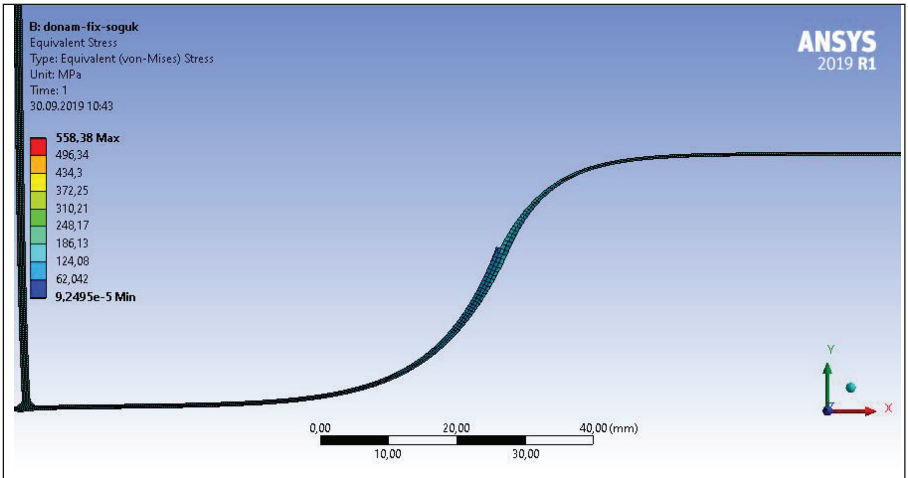


Figure 7. The Reaction of the Cold Inner Tank Bottom Plate When The Shell is Warm (closer to the shell)

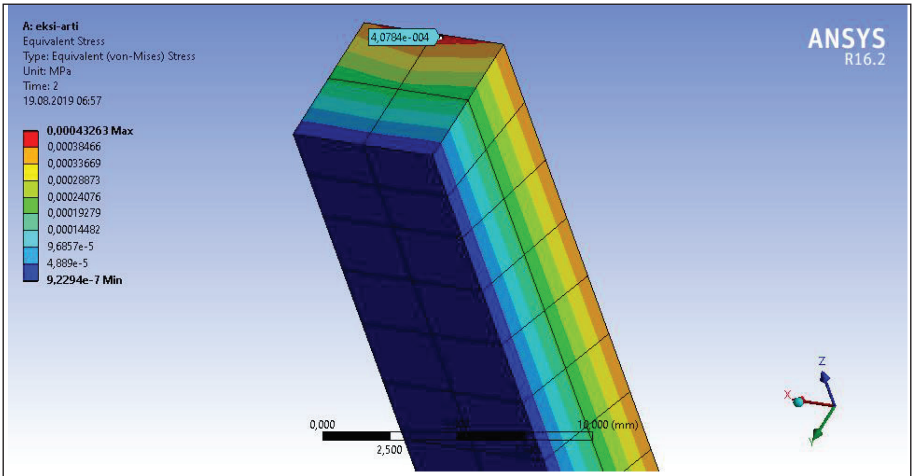


Figure 8. Determination of Residual Stress in the Bottom Plate Strip Nonlinear Analysis at the End of One Cycle

much at the wall (shell) level. The 157 MPa principal stress encountered in the 6 mm thick bottom plate or the 190 MPa obtained in terms of the von Mises stress is below the level that will cause plastic deformation, considering that the yield strength is 220 MPa.

When there was no product in the tank, non-linear analysis was performed, in which the temperature of the tank bottom plate was reduced from ambient temperature to -33°C and then brought back to ambient temperature, it was observed that plastic deformation did not occur (Figure 8). In the figure, it is seen that there is no significant residual stress in the bottom plate strip, and the stress is decreasing from the upper (product) surface of the plate to the lower surface.

4. THE FULL CONDITION OF THE TANK

Consider that the product is taken to the tank as specified by the Code and the tank reaches a full state (Figure 9). In this case, besides the hydrostatic pressure at the bottom of the tank and the first shell, the contraction movement of the shell will be completed.

The tank is operating at approximately 127 mbarg. If the pressure exerted by the weight of the product on the tank bottom plate, the presure is found as 2.5 atm (0.25 MPa) as a result of Eq. 3:

$$P = P_0 + \rho g h \tag{3}$$

The stress exerted by the hydrostatic pressure on the shell causes Hoop's or meridional

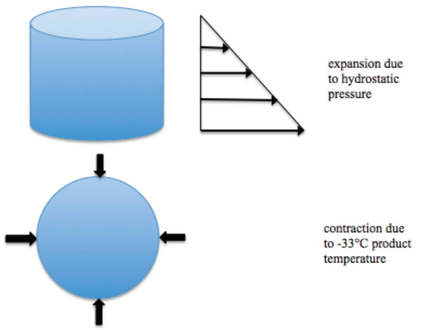


Figure 9. The Expansion and Contraction of tThe Bottom Plate and Shell At Full Condition

stress. The stress also causes the change in diameter. According to API Standard 653, the pressure applied to the shell near the bottom plate is calculated as 126 MPa using Eq. 4. Here, D is the diameter of the tank in feet, H is the height of the product in feet, G is the specific gravity of the product (0.68), and t is the wall thickness of the first shell in inches.

$$P = \frac{2.6\,DGH}{t} \tag{4}$$

The pressure found tries to expand the diameter of the tank at a height of approximately 300 mm from the bottom of the tank when the tank is full. As can be seen from the calculation below, the nominal diameter of the tank, which is 29,650 mm, increases by 18 mm as a result of Eq. 5:

$$\sigma = \varepsilon E \tag{5}$$

When the tank is full with the product at a temperature of -33°C, the thermal shrinkage of the bottom plate is balanced with the shrinkage of the shell. But, the shell of the tank is also exposed to hydrostatic pressure. The diameter of the tank will increase by $\delta=0.024P=18$ mm. An increase of 18 mm in diameter induces a stress of 123 MPa and 92 MPa in the bottom and annular plate, respectively. In Figure 10, it can be seen that there is little stress difference in the strip between the near shell and the center of the tank, and it is higher in the central part.

The stresses encountered are below the yield stress when the tank is at full condition. As a result of the non-linear analysis based on this state, it is seen that the von Mises stress gives a result close to the calculated value as seen in Figure 10.

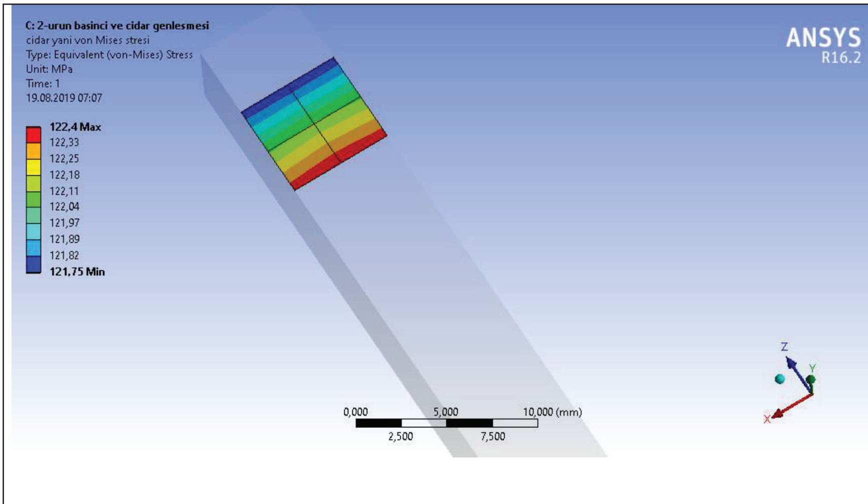


Figure 10. The von-Mises Stress Distr. Of The Bottom Plate Strip Adjacent to The Shell When the Tank is Full

5. THE HALF-FULL TANK SITUATION IN WHICH THE PRODUCT IS TAKEN QUICKLY

The plastic deformation problem encountered originates from the stress when the tank is at intermediate levels or full condition but the temperature regime has not been reached. In the tank, the surface area of the inner shell is approximately three times the inner bottom plate area. Although the shell thickness varies along the height of the tank, it has an average thickness of 10.4 mm and is approximately 1.72 times the thickness of the bottom plate. Considering the insulation loss, it is not easy to reduce the surface temperature of the shell plate. The cooling of the shell is approximately six times slower than that of the bottom plate. When the bottom plate surface temperature drops by 60°C, the temperature of the shell surface will drop by 10°C.

Consider the situation that the 1/3 of the tank is filled quickly and the temperature of the shell drops from 30°C to 20°C. In this case, the tank will try to adapt to the aforementioned contraction of the bottom plate by cooling down of the shell by 10°C, but the hydrostatic pressure of approximately 10 m height liquid ammonia to the bottom-shell junction will also cause to expansion of the bottom plate. The contraction of the shell due to temperature drop by 10°C is calculated as 11.46 mm and the diameter is reduced by 4 mm to 29,646 mm. This will relieve the tank bottom plate and reduce the stress value. However, the hydrostatic pressure of 63 MPa created by the liquid ammonia at the bottom of the first shell increases the diameter by 10 mm. In this case, there will be a total increase of 6 mm. This stress expands the bottom plate 6 mm in diameter, which is trying to thermally shrink, now reaches the critical threshold of

1190 N load. The maximum principal stress that this load will create on the bottom and the annular plate will be 200 MPa and 150 MPa, respectively. As can be seen, the resulting stress of 200 MPa is quite close to the yield strength of 220 MPa.

It is possible to reach the following intermediate results from all this analytical work:

a. When the tank is put into service at a slow level, there is no problem in the tank,

b. When the tank is put into service quickly, the yield strength can be reached in the bottom plate. The plastic deformation of the bottom plate is due to the fact that the tank shell cannot reach a sufficient temperature regime.

6. EVALUATION OF THE FIELD FINDINGS

The fact that the bottom plate has a wavy structure at the end of plastic deformation can lead to some mistakes for the tank owners in the evaluation according to the Standard in the first place. The wavy structure of the bottom plate was evaluated as the 'bulges' specified in Annex B2 of the API Standard 653. Therefore, it was concluded that the bottom plate should be renewed as it exceeds the bulge limit specified by the Standard. But, bulge is a subject related the erosion of the insulation material under the bottom plate. The recess or bulge is dangerous when the tank is full because there is no contact between the floor (bottom) plate and the structure below it (Figure 11). However, there is no erosion problem in the sub-insulation structure of the tank in question and is related to the plastic deformation of the bottom plate.

The bottom plate consists of a number of plates that are overlap welded on each other. A limit of plastic deformation due to thermal stress is also specified in B4.2 of the Code. In the Code, it is stated that those that have undergone 2-3% plastic deformation should be replaced.

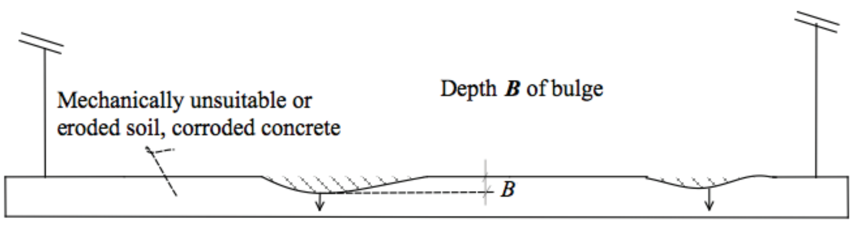


Figure 11. Assessing Bottom Bulges: API 653 B-2.4 and B-2.5 [17]

7. EVALUATION OF THE PLASTICALLY DEFORMED BOTTOM PLATE

Tensile and impact analysis were carried out by cutting a piece in the form of a 200 mm square from the bottom plate where the deformation occurred at the most. The chemical composition of the material was also determined. The yield strength of the plate was found as 358 MPa, and the average toughness value was found to be 66.7 J as a result of the impact test performed at -40°C. The patch plate placed on the cut is P265GH material in the Specification of EN10028-2 [18] and the mechanical feature of this material is presented in Table 3.

Table 3. Tank Bottom and Patch Plate Mechanical Test Results

Sample	F_{max} (kN)	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Thickness (mm)	Toughness (J) (-40 °C)
Original bottom plate	61.4	512	358	30.6	5.99	66.7
Patch plate	56.9	474	292	29.7	6	59.3

It can be seen from the table that the bottom plate sample, which has been already undergone elasto-plastic deformation, has higher (toughness) values than P265GH patch plate. In terms of toughness, the relevant Code requires a minimum of 20 J impact strength of the material at -40°C. With its 66.7 J value, it is seen that there is no problem at this point. From the point of yield strength, it can be considered that a higher tough material than the material of the patch plate (P265GH) is used. When the projects of the tank are examined, bottom plate was constructed from ASTM A516 Gr 60 material quality and is equivalent to P265GH. Although ASTM states the yield strength as 220 MPa, it is determined that the yield strength is 265 MPa in the data of many manufacturers and in the P265GH material. In any case, the 358 MPa encountered is the yield value due to the Bauschinger effect and does not reflect the original yield value of the material.

8. THE BAUSCHINGER EFFECT

As seen in Figure 12, when a stress Y' above the yield stress Y is applied to a material and the stress is removed, the elastic stress path of this material under the stress will now be OYY', the new yield strength Y' and plastic deformation OO' [19].

A material that has exceeded its yield strength or has undergone plastic deformation is not completely in an undesired condition. However, it should be noted that the area under the stress-strain curve gradually decreases as a result of plastic deformation. The curve follows the path O'Y', and the area OO'YY' is lost. The API-653 Code

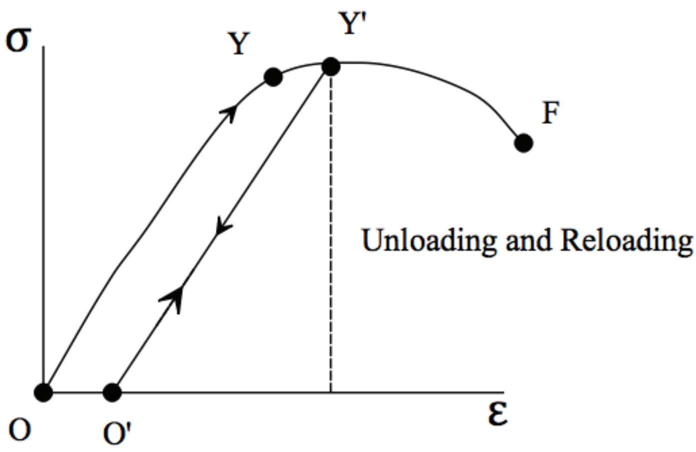


Figure 12. The İncrease in Yield Strength of The Material by the Bauschinger Effect

requires the replacement of the relevant bottom plates in the case of an average of 2.5% plastic deformation. Assume that the yield strength of the bottom plate used in the tank is 265 MPa and a new yield strength of 358 MPa has been reached due to strain hardening, and in this case, the percentage of plastic deformation needs to be determined by using the Ramberg-Osgood criterion [20].

The stress-strain (strain) curve is consisting of the sum of the elastic and plastic regions. The elastic region has Hook's slope, while the plastic region can be found approximately by the Ramberg-Osgood criterion. The stress-strain relationship in the plastic region has the following exponential function (Eq.6). Here, ε_p, is the plastic elongation, *H* is the strength coefficient, and "*n*" is the strain hardening coefficient.

$$\sigma = H\varepsilon_p^n \tag{6}$$

So, the total elongation is

$$\varepsilon = \varepsilon_e + \varepsilon_p \tag{7}$$

$$\varepsilon = \frac{\sigma}{E} + \left[\frac{\sigma}{H}\right]^{1/n} \tag{8}$$

H and n in this equation can be found by using the Eq.9 and 10, which indicates tensile σult and yield strength σy, respectively:

$$n = \frac{\log\left(\sigma_{ult} / \sigma_y\right)}{\log\left(\varepsilon_f / 0.002\right)} \quad (9)$$

$$H = \frac{\sigma_y}{0.002^n} \quad (10)$$

In the equation,ε_f, shows the total elongation that occurs when the material breaks and can be found with the Eq.11:

$$\varepsilon_u = \varepsilon_f + \frac{\sigma}{E} \quad (11)$$

The stress, strain and modulus values of the tank bottom plate material are given in Table 4.

Table 4. The Stress, Strain and Modulus of The Tank Bottom Plate

Data	Value
σ_{ult}	512 MPa
σ_y	265 MPa
ε_u	0.3059 mm/mm
E	200 000 MPa

Based on these data, it is seen that the plastic elongation εf is 0.3034 mm/mm. The strain hardening coefficient "n" and the coefficient of strength H are calculated as 0.1312 and 598.9 MPa, respectively. After revealing these values, it can be concluded that the total elongation that occurs when the yield strength of 358 MPa is reached is 0.02117 mm/mm. When the elastic elongation is deducted from the total elongation, the plastic elongation amount of 0.01938 mm/mm is encountered. This figure shows us that if the material reaches a yield strength of 358 MPa, the plastic deformation is about 1.938 %. To be remembered, the API-653 Code was pointing to the rate of 2-3% to change. Considering the average of 2.5%, it shows that the encountered plastic deformation approached the limit and that it is necessary to be very careful especially when taking the first product (ammonia) into the tank.

Safety is very important. However, correct evaluation and economic approach are also important concepts. It would be an economical safe way to choose the plastic deformation analysis way instead of the B2 appendix of the Code in the evaluation of the plastic deformation at the bottom of the tank.

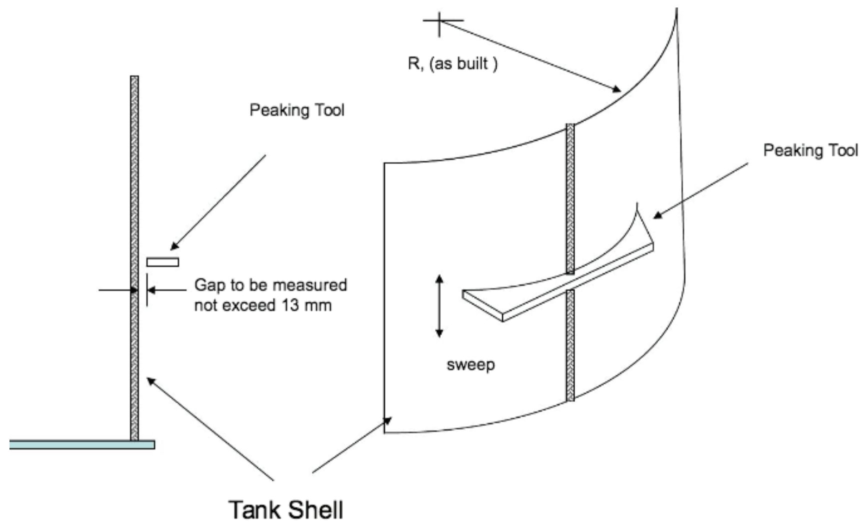


Figure 13. API Standard 650 Shell Constructing Steepness-Ovality Control [12]

When examining the verticality problem in the tank's shell, the steepness was thought as not suitable because it is more than 13 mm according to the API Standard 650 (Figure 13). But, in the standard, this issue is specified for the inspection of the shell that need to be bent according to the radius of the tank during construction. Hence, this issue was misunderstood. If there is a problem in the radius of curvature before the welding of the shell plates, it should be measured with the help of a gauge and if it exceeds ½ inch, the spot welding should be removed, the sheet should be straightened and put back in place. There is no such situation in the tank, because the thermal movements of the shell and the bottom plate cannot be synchronized due to rapid product intake into the tank, and in addition, the anchor rods and wind beams around the outer perimeter of the shell prevent the bending.

The yield strength of A516-70 material is 37,700 Psi (260 MPa). When the tank is full of product, the stress at the lower part of the first shell is 126 MPa. The stress caused by the weights of the above shell plates on the first shell is at the level of 0.93 MPa. It does not seem possible that a situation such as buckling or bending can occur in the first shell, which is supported by anchorages from the outside, with careful use after this point.

The Occupational Health and Safety Law states that above-ground storage tanks where dangerous substances are stored should be checked every 10 years. If the design data of the ammonia tank is selected and maintained in accordance with the process and its external maintenance is fully carried out, there is actually no reason to enter it.

The more frequent internal maintenance is taken, the higher the probability of encountering undesirable situations. In terms of thermal stress, being constantly at -33°C is much better than bringing it from -33°C to ambient temperature. However, after all these observations in this case, it would be more safe approach to act according to the risk analysis directive published by EFMA [4] and to schedule the next maintenance date accordingly.

9. CONCLUDING REMARKS

The plastic deformation of the bottom plate of the tank and the deformation of the shell due to thermal shrinkage brought to mind that the tank should undergo a major repair in the first place. The failure of such important tanks in chemical plants causes the production of the plant to be interrupted. However, the root-cause analysis study and the calculations have shown that the tank can be used after this stage with careful use.

From here, it is possible to reach the following results:

a. Cooling or heating the tank at 1°C/h is important to avoid plastic deformation,
b. perties. The material, which is completely plastically deformed, cannot fulfill its load-bearing function. This situation also showed itself in the hydrostatic pressure test performed with water at a height of 12 m during the maintenance, and no leakage was encountered. At the end of the hydrostatic test, it was also determined that the bottom plate was flattened to a large extent,
c. Slow commissioning and use of the tank in accordance with the Code will increase the service life of the existing material,
d. The percentage of plastic deformation in the tank was determined as 1.94%. It is a value that is close to the limit, but does not require a change,
e. Occupational Health and Safety legislation requires that tanks where dangerous substances are stored be subject to internal control once every 10 years. However, importance is also attached to risk-based analysis. Instead of risk-based analysis, the internal control to be carried out once in 10 years will decrease the life of the tank and increase the maintenance costs. However, due to the delicate condition of the tank in this case, it may be more robust to think of the third maintenance after 10 years of the second one.

ACKNOWLEDGEMENT

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

1. API Standard 620, Design and Construction of Large, Welded, Low-Pressure Storage Tanks, Twelfth Edition, Oct. 2013.
2. EN 14620, Design and manufacture of site built, vertical, cylindrical, flat-bottomed steel tanks for the storage of refrigerated, liquefied gases with operating temperatures between 0°C and -165°C - Part 1-5,
3. **Jeremić, L., Đorđević, B., Šapić, I., Sedmak, S.A., Milovanović, N.** Manufacturing and Integrity of Ammonia Storage Tanks, Struct. Integ. and Life, 20(2): 123-129, 2020.
4. Guidance For Inspection of Atmosferic, Refrigerated Ammonia Storage Tanks, European Fertilizer Manufacturers Association, Second Edition, Belgium, 2008 Edition, Issue 2014.
5. **Baboo, P.** Ammonia Storage Tank Pre -Commissioning. International Journal of Engineering Research and Technology, 2019. https://doi.org/10.17577/ijertv8is090209
6. **Orooji, A., Hosseininna, S.S.** Lessons Learned From Decommissioning of a Liquid Ammonia Storage Tank, Asian Nitrogen + Syngas 2014 International Conference, Jakarta, Indonesia, 17 - 19 November 2014.
7. Benac, D.J., Cherolis, N.E., & Wood, D.F., Managing Cold Temperature and Brittle Fracture Hazards in Pressure Vessels. Journal of Failure Analysis and Prevention, 16, 55-66, 2016. https://doi.org/10.1007/s11668-015-0052-3
8. **Lonsdale, H.** in Ammonia Tank Failure, Ammonia Plant Safety AIChE, vol. 17. pp. 126–131, South Africa, 1975.
9. **Sweat, M.E.** An ammonia tank failure. A nuts-and-bolts account, covering the cause of failure, repair, and procedural changes made to prevent recurrence. Plant/Oper. Prog., 2: 114-116, 1983. https://doi.org/10.1002/prsb.720020210
10. **Loginow, A.W.** A review of stress corrosion cracking of steel in liquefied ammonia service. Materials Performance, 25, 18-22, 1986.
11. **Malhotra, P.K., Veletsos, A.S**. Uplifting Analysis of Base Plates in Cylindrical Tanks. Journal of Structural Engineering-asce, 120, 3489-3505, 1994. https://doi.org/10.1061/(ASCE)0733-9445(1994)120:12(3489)
12. API Standard 650, Welded Tanks for Oil Storage, Twelfth Edition, March 2013.
13. **Lele, G.S.** Ammonia Storage: Selection & Safety Issues, Chemical Industry Digest., May 2008.
14. **Al-Abdulally, F., Al-Shuwaib, S. and Gupta, B.L.** Hazard Analysis and Safety Considerations in Refrigerated Ammonia Storage Tanks, Plant/Operations Progress, Wiley Online Library, Vol. 6, Issue 2, p. 84-88, 1987. https://doi.org/10.1002/prsb.720060209

15. API Standard 653, Tank Inspection, Repair, Alteration, and Reconstruction, Fifth Edition, November 2014.

16. ASME Boiler and Pressure Vessel Code, Section II-Materials, Part D- Properties, Table 1A, 2017 Edition.

17. **Matthews, C.** A Quick Guide to API 653 Certified Storage Tank Inspector Syllabus, Woodhead Publishing Limited, 2011.

18. EN10028-2:2017, Flat products made of steels for pressure purposes - Part 2: Non-alloy and alloy steels with specified elevated temperature properties.

19. **Lee, M., Barlat, F.** Modeling of Plastic Yielding, Anisotropic Flow, and the Bauschinger Effect, Material Science, 2014. https://doi.org/10.1016/B978-0-08-096532-1.00219-3

20. **Ramberg, W., Osgood, W. R.** Description of stress–strain curves by three parameters. Technical Note No. 902, National Advisory Committee For Aeronautics, Washington DC, 1943.