



Operational Feasibility Analysis of Propane Storage Tank Due to Subsidence

Nathan Samuel Bhagaskara¹, Rachman Setiawan¹ & Ade Nadjuri^{1,2}

¹Faculty of Mechanical and Aerospace Engineering, Institut Teknologi Bandung, Jl. Ganesha, 10, Bandung, 40132, Jawa Barat, Indonesia

²EPCC Division, PT. Wijaya Karya (Persero) Tbk., Wika Tower II Jl. DI Panjaitan, Kav. 9-10, Jakarta Timur, 13340, DK Jakarta, Indonesia
r.setiawan@itb.ac.id

Abstract. During hydrostatic testing, an 80,000 m³ propane storage tank exhibited subsidence, causing deformation of its outer shell. This necessitated an evaluation of the tank's operational viability and fitness for service, guided by API 579-1/ASME FFS-1 procedures. The assessment started with Level 1 and Level 2 analyses using distortion measurements, and if needed, progressed to Level 3 for detailed numerical analysis. Results from Levels 1 and 2 indicated acceptable out-of-roundness ($RSF \geq RSFa$) and out-of-plumbness ($1/200 h_{\text{tank}}$) but not bulging, leading to further analysis through elastic-plastic finite element simulation at Level 3. Although stresses exceeded yield strength, the tank was deemed fit for service under plastic collapse and local failure criteria, maintaining buckling stability. Operational recommendations include addressing wind, seismic, and pressure loads and reinforcing and regularly monitoring the shell to ensure ongoing safety and structural integrity.

Keywords: Propane storage tank; subsidence; distorted tank; elastic-plastic analysis; finite element simulation.

1 Introduction

Storage tanks at a refinery store liquids and/or gases such as methane, ethane, propane, butane, and others (Amorin et al., 2018) [1], (Liu et al., 2020) [2]. These substances are stored in large volumes and subsequently distributed to companies that require them. In particular, tanks must be designed with safety in mind and undergo inspection, examination, and testing before they can be fully operational for the storage of toxic and hazardous substances (Amorin et al., 2018) [1], (Liu et al., 2020) [2].

Storage tanks are designed according to specific codes and standards, which contain regulations that must be followed in the design of mechanical installations (Amador, 2004; Djermane et al., 2014; Jaiswal et al., 2007; Maraveas & Miamis, 2013; Sengara et al., 2019; Spritzer & Guzey, 2017; Sutjipto, 2011) [3]–[9]. Generally, two commonly used codes and standards for the design of storage tanks are the American Petroleum Institute (API) 620 and API 650 (American Petroleum Institute, 2019) [10]. The difference between these codes lies in the type of substances stored: API 620 can withstand higher pressures and lower temperatures than API 650.

Even when a storage tank is designed according to standards, failures can still occur. Such failures can degrade the tank's performance or even render it unfit for use. To determine a storage tank's suitability, assessments are needed in accordance with API RP 579/ASME FFS-1 Fitness for Service (FFS) (Anderson & Osage, 2000) [11]. FFS is a quantitative engineering assessment conducted to evaluate the structural integrity of equipment that is in operation and has experienced defects and/or failures. Some notable research about this issue has been done by (Amorin et al., 2018; API STD 620:2021-09 Design and Construction of Large, Welded, Low-Pressure Storage Tanks, 2019; Bai & Lin, 2015; Djermane et al., 2014; Hotala & Ignatowicz, 2019; Jäger-Cañás & Pasternak, 2017; Liu et al., 2020; Maraveas & Miamis, 2013; Morita et al., 2003; Stein & Housner, 1978; Teng & Rotter, 2004; Virella et al., 2006; Zhao et al., 2013) [1], [2], [18]–[20], [7], [8], [12]–[17]. However, it is limited to parametric studies and load assumptions. Based on the author's knowledge, no research has been done using actual data and factual tank subsidence.

In this paper, a study case of a storage tank designated T-201, designed to hold propane, experienced subsidence during hydrostatic testing. As a result of this subsidence, the outer wall of the tank became distorted. Failure due to subsidence in a storage tank can occur as a result of design errors, improper location selection for the tank installation, or various other external factors. In this analysis, the author will conduct a fitness-for-service assessment of the propane storage tank to evaluate its suitability after experiencing subsidence.

2 Analysis by Code

2.1 Tank Design

The storage tank T-201 under study was designed according to the API 620 code and standard. It has a height of 30.1 meters and a diameter of 64 meters. It contains liquid propane with a nominal capacity of 80,000 cubic meters, as shown in Figure 1.



Fig. 1. Propane storage tank T-201 under construction

The T-201 tank consists of an inner and outer section separated by an insulating layer to maintain the propane at a low temperature. The outer section includes 12 shell courses connected to the tank's base, which is composed of an annular ring and a bottom plate, while the top section is connected to the roof structure and roof plate. Table 1 Provides the thickness and material specifications of each component.

Table 1. Propane storage tank material and thickness

Component		Material	Thickness(mm)
Roof Plate		A283-C	6,5
Stiffener ring		A36	L200
Roof Structure			WF250
Shell Course	12	A516 Gr.60	38
	9-11	A283 Gr.C	14
	4-8		15
	2-3		16
	1	A516 Gr.60N+S5	
Bottom Plate		A516 Gr.60	6,5
Annular Plate		A516 Gr.60N+S5	12

The layout of the T-201 propane storage tank is depicted in Figure 2.

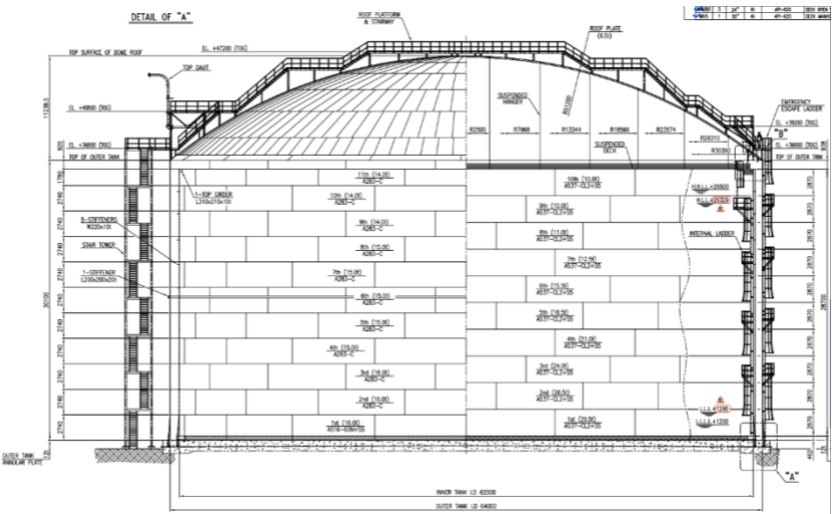


Fig. 2. General arrangement view of propane storage tank T-201

Courses 1 through 10 each have a height of 2,740 mm, course 11 is 1,780 mm, and course 12 is 920 mm. A stiffener ring is installed at course 6 to reinforce the tank's

structure. Each material used in the tank possesses distinct mechanical properties listed in Table 1. The yield strength and maximum tensile strength of the material A516 Gr.60N+S5 were obtained from mill tests. The values for Young's modulus, density, and Poisson's ratio were unavailable and thus are assumed to be the same as those for A516 Gr.60.

2.2 Subsidence Data

Due to the tank's weight during construction, ground settlement, commonly referred to as subsidence, occurred. A hydro test was then conducted to test the tank's resistance to leakage. However, during the hydro test, the tank experienced further subsidence. The ground continued to settle for several hours following the initial subsidence. The extent of ground settlement was measured using a theodolite, as shown in Figure 4 presents the subsidence data for the tank, measured in the field using the theodolite.



Fig. 3. Theodolite measurement on to the propane storage tank T-201

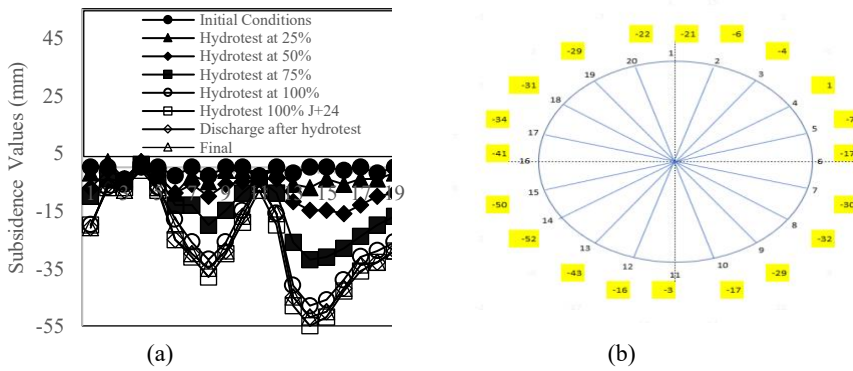


Fig. 4. Subsidence of the propane storage tank T-201 foundation, (a) data, (b) position

2.3 Storage Tank Measurement

The subsidence condition caused distortion in the storage tank walls. The outer tank wall was measured using a string line and a laser drone 3D scanning method. A string line is a tool similar to a spirit level, capable of measuring over longer distances with a string, the string line measured radial deformation on the outer tank wall. Figure 5 illustrates the measurement process using a string line on the storage tank wall.



Fig. 5. Propane storage tank T-201 shell measurement using string line

The 3D scanning method involved using a drone to capture the tank’s contours and record the results visually and coordinately. Measurements with the string line were conducted at 45° and 180° orientations. At the 45° orientation, field measurements were taken only on shell courses 1–6, while at the 180° orientation, measurements were taken on shell courses 1–10. The measurement results using the string line at both the 45° and 180° orientations are shown in Figure 6.

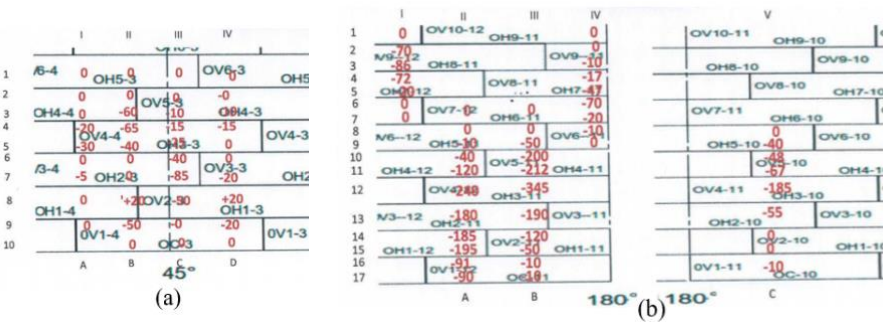


Fig. 6. The measurement result from the string line at the orientation (a) 45° and (b)180°

Figure 7 and Table 2 present the results from the laser drone 3D scanning of the storage tank. The contour visualization data are available only for the 180° orientation. The processed diameter measurements for each shell course are provided in Table 2.

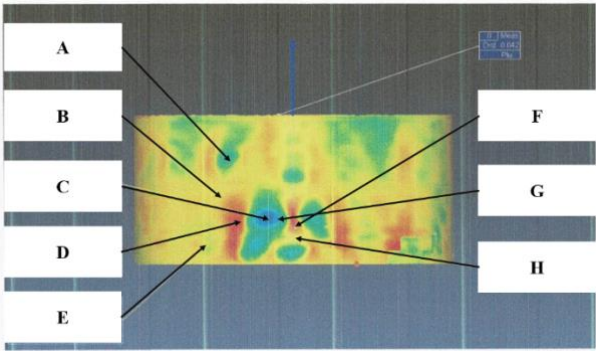


Fig. 7. 3D laser drone scanning at orientation 180°

Table 2. The measured deviation values of the outer wall of storage tank T-201 using laser drone 3D scanning at the 180° orientation.

Id	Measurement axis-			3D Deviation (m)
	x (m)	y (m)	z (m)	
A	293.9190	-28.9537	20.9102	-0.1063
B	291.0681	-27.6092	13.7630	0.0171
C	302.1396	-31.2146	8.7275	-0.3086
D	295.4206	-29.8015	7.7879	0.1025
E	291.2008	-27.1120	5.0903	0.0043
F	307.5465	-32.0092	6.9320	0.0851
G	304.3710	-31.5991	8.4670	-0.2015
H	308.0116	-31.9163	4.5906	0.0096

2.4 Level 1 Investigation

The secondary data shows that the results of the 3D scanning measurement of the outer wall diameter of tank T-201 are non-uniform. For a Level 1 assessment, data on the maximum diameter, minimum diameter, and plumbness of the tank wall, which has undergone subsidence, are required. The following are the 3D scanning results for the necessary data for the Level 1 assessment.

- Maximum Diameter : 64,2601 m
- Minimum Diameter : 63,4062 m
- Plumbness : 41,99 mm

This data is then used to conduct the Level 1 assessment in accordance with API 579-1/ASME FFS-1 fitness-for-service, which is shown in Table 3.

Table 3. Level 1 fitness-for-service examination

Level 1					
<u>Out-of-Roundness for Tank Shells</u>					
Data	Value	Unit	Remarks	Comply standard	to
Storage Tank Diameter	64,000	mm	Before Subsidence	-	
After Subsidence Measurement					
Minimum Diameter	63.4062	m	Field data taken from 3D Scanning	-	
Maximum Diameter	64.2601	m			
	0.85386	m	-		
Deviation	853.86	mm	Maximum according to standard: 300 mm	NO	
Percentage of the storage tank diameter	1,33	%	Maximum according to standard: 1%	NO	
<u>Out-of-Plumbness for Tank Shells</u>					
Data	Value	Unit	Remark	Comply standard	to
Plumbness	0	mm	-	-	
After Subsidence Measurement					
Measured Plumbness	41,99	mm	Maximum according to standard: h/200 mm = 150.5 mm	YES	

Based on the Level 1 assessment results, as shown in Table 3, the storage tank does not meet the acceptance criteria (853.86 mm; 1.33%) for the out-of-roundness category, as it exceeds the standard limit (300 mm; 1%). Therefore, the assessment for the out-of-roundness category must proceed to a Level 2 evaluation.

For the out-of-plumbness category, it was determined that the storage tank meets the acceptance criteria (41.99 mm) because it does not exceed the standard limit (150.5 mm).

Of the two categories used for assessment, one (out-of-roundness) did not meet the standard, while the other (out-of-plumbness) did. Despite one category meeting the criteria, the analysis will continue to a Level 2 assessment for the out-of-roundness category.

2.5 Level 2 Investigation

The assessment proceeds to Level 2 after the Level 1 acceptance criteria are unmet. The categories evaluated in the Level 2 assessment are out-of-roundness for the cylindrical shell and bulges.

STEP 1 – DETERMINATION OF PARAMETERS

The values of the parameters used in the Level 2 assessment are presented in Table 4 and Table 5.

Table 4. Parameter for FFS level 2

No	Symbol	Value	Unit	Remark
1	θ	0 or 90	Degree	Taken for critical result $\cos(2\theta)$ (minimum or maximum)
2	C_s	0.1	-	0,5 for oval shape 0,1 for other than oval shape
3	D_m	1	in	
		2-3		
		4-8		
		9-11		
		12		
4	D_{ma} x	1	in	-
		2-3		
		4-8		
		9-11		
		12		
5	D_{min}	1	in	
		2-3		
		4-8		
		9-11		
		12		

No	Symbol		Value	Unit	Remark
6	E		1	-	
7	E _y	Material	A283-C	28,862,509.	psi
			8		
			A516 Gr. 60	28,993,043.	
			A516 Gr. 60N+S5	8	
8	FCA		0		
9	LOSS		0	in	
10	P		2.134	psi	
¹ 1	R		1,259.84	in	

Table 5. Parameter for FFS level 2 (ctd)

No	Symbol		Value	Unit	Remark
12	S	Material	A283-C	15.200	psi
			A516 Gr. 60	18.000	
			A516 Gr. 60N+S5	20.711,389	
13	t _{nom}	Shell course	1-3	0,63	in
			4-8	0,59	
			9-11	0,55	
			12	1,50	
			1-3	0,63	
14	t _{rd}	Shell course	4-8	0,59	in
			9-11	0,55	
			12	1,50	
15	v	Material	A283-C	0,29	-
			A516 Gr. 60		
			A516 Gr. 60N+S5		

STEP 2 – WALL THICKNESS FOR ASSESSMENT (tc)

To determine the wall thickness used in the Level 2 assessment, Eq. 1 and Eq. 2 are applied.

$$t_c = t_{nom} - LOSS - FCA \tag{1}$$

$$t_c = t_{rd} - FCA \quad (2)$$

These two equations are then compared, and the minimum value is selected. The measurement and design values for LOSS and FCA are 0, as shown in Table 4, items 8 and 9. Therefore, the value of t_c equals t_{nom} and t_{rd} for each shell course, as indicated in Table 5, items 13 and 14.

STEP 3 – CIRCUMFERENTIAL MEMBRANE STRESS

Two steps must be performed to determine the circumferential membrane stress: circumferential stress and longitudinal stress, as illustrated in Figure 8.

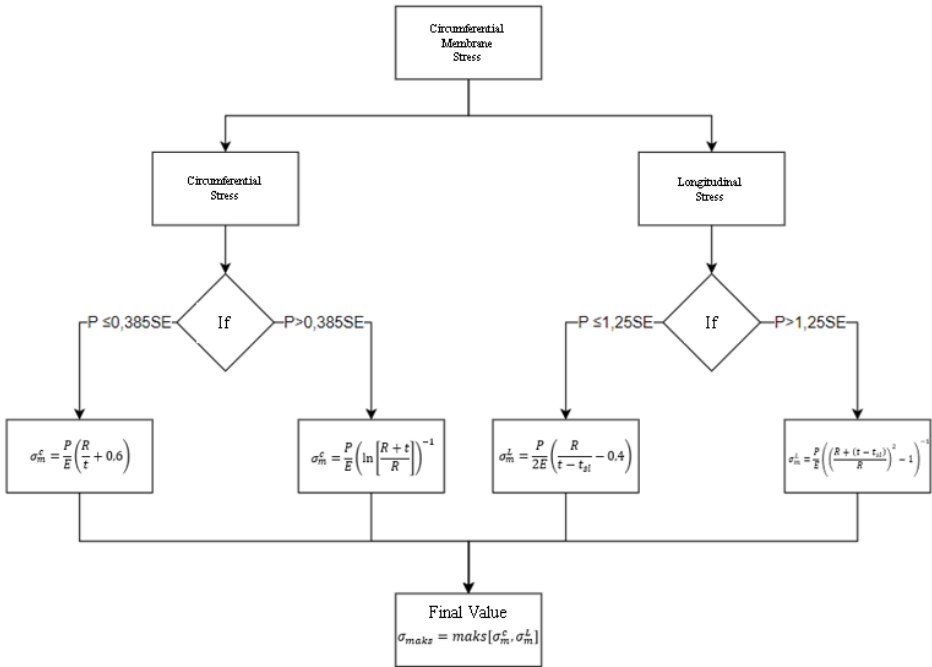


Fig. 8. Flow chart of circumferential membrane stress selection

To determine the circumferential stress, it must first be determined whether the value of P is greater or less than $0.385SE$. Based on Table 4, Table 7 indicates whether P is greater or less than $0.385SE$.

Table 6. Determining whether the condition P is greater than or less than $0.385SE$

Material	Symbol		Remark
	P	0,385SE	
A283-C	2.134	5852	$P \leq 0,385SE$
A516 Gr. 60		6930	

Material	Symbol		Remark
	P	0,385SE	
A516 Gr. 60N+S5		7973,88	

Table 7 shows that $P \leq 0.385SE$, so the circumferential stress equation used is Eq. 3.

$$\sigma_m^c = \frac{P}{E} \left(\frac{R}{t} + 0,6 \right) \tag{3}$$

To determine the longitudinal stress, whether P is greater or less than 1.25SE must first be established. Based on Table 6, Table 7 shows whether P is greater or less than 1.25SE.

Table 7. Determining whether the condition P is greater than or less than 1.25SE

Material	Symbol		Remark
	P	1,25SE	
A283-C		19000	
A516 Gr. 60	2.134	22500	$P \leq 1,25SE$
A516 Gr. 60N+S5		25889,2	

Table 7 shows that $P \leq 1.25SE$, so the longitudinal stress equation is Eq. 4.

$$\sigma_m^L = \frac{P}{2E} \left(\frac{R}{t - t_{sl}} - 0,4 \right) \tag{4}$$

The larger value between the circumferential and longitudinal stresses is selected as the circumferential membrane stress. Table 8 presents the circumferential stress, longitudinal stress, and circumferential membrane stress for each shell course.

Table 8. Circumferential membrane stress

Shell Course	σ_m^c (psi)	σ_m^L (psi)	Maks (σ_m^c , σ_m^L)
1-3	4,269.27	2,133.57	<u>4,269.27</u>
4-8	4,553.8	2,275.84	<u>4,553.8</u>
9-11	4,878.98	2,438.43	<u>4,878.98</u>
12	1,798.33	898.098	<u>1,798.33</u>

STEP 4 – RATIO OF CIRCUMFERENTIAL BENDING STRESS TO CIRCUMFERENTIAL MEMBRANE STRESS

To determine the ratio of circumferential bending stress to circumferential membrane stress, Eq. 5 is used.

$$R_b^{or}(\theta) = \frac{1,5(D_{maks} - D_{min})\cos[2\theta]}{t \left(1 + \left[\frac{C_s P (1 - \nu^2)}{E_y} \right] \left[\frac{D_m}{t_c} \right]^3 \right)} \quad (5)$$

The value of θ for $\cos(2\theta)$ is selected at the critical points, which occur at 0° and 90° , as shown in Table 4, item 1. The ratio of circumferential bending stress to circumferential membrane stress is presented in Table 9.

Table 9. $R_b^{or}(\theta)$ Value

Shell Course	Orientation	$R_b^{or}(\theta)$
1	0°	<u>0,11</u>
	90°	<u>-0,11</u>
2-3	0°	<u>0,16</u>
	90°	<u>-0,16</u>
4-8	0°	<u>0,16</u>
	90°	<u>-0,16</u>
9-11	0°	<u>0,07</u>
	90°	<u>-0,07</u>
12	0°	<u>0,25</u>
	90°	<u>-0,25s</u>

STEP 5 – REMAINING STRENGTH FACTOR (RSF)

To determine the remaining strength factor, Eq. 6 is used.

$$RSF = \min \left[\left\{ \frac{H_f S_a}{\sigma_m(1 + R_b) + \sigma_{ms}(1 + R_{bs})} \right\}, 1 \right] \quad (6)$$

The value of S_a depends on the material type of the shell, as indicated in Table 5, item 12. The value of σ_m is the circumferential membrane stress shown in Table 8. The value of the variable H_f is provided in API 579-1/ASME FFS-1 as 1.5. Since the value of R_{bs} is -1, the result of $\sigma_{ms}(1 + R_{bs})$ is 0. The RSF results are presented in Table 10.

Table 10. RSF Value

Shell Course	Orientation	RSF	
1	0°	min(6,539; 1)	<u>1</u>
	90°		
2-3	0°	min(4,61; 1)	
	90°		
4-8	0°	min(4,313; 1)	
	90°		
9-11	0°	min(4,388; 1)	
	90°		
12	0°	min(12,038; 1)	
	90°		

STEP 6 – ACCEPTANCE CRITERIA

For the Level 2 assessment, with an RSF_a value of 0.9. The results of the Level 2 assessment are presented in Table 11.

Table 11. Level 2 investigation result

Shell Course	Orientation (°)	Requirement	RSF Value	RSF _a	Comply
1	0	RSF ≥ RSF _a	1	0,9	Comply
	90				
2-3	0				
	90				
4-8	0				
	90				
9-11	0				
	90				
12	0				
	90				

Based on the Level 2 assessment calculations, the storage tank is suitable for the out-of-roundness category because the remaining strength factor exceeds the standard requirement. However, the bulge failure category cannot be evaluated in a Level 2 assessment because calculations are not provided in API 579-1/ASME FFS-1, as

indicated in Section 8.4.3.6 of the API 579 standard. Therefore, the assessment will proceed to Level 3 using elastic-plastic analysis methods.

3 Numerical Analysis

3.1 Storage Tank Modeling

The storage tank's geometric modeling was conducted using Space Claim within ANSYS. The components, including the wall, base plate, annular plate, and roof plate, were modeled using shell element models. Meanwhile, the roof structure and stiffener rings were modeled using H-beam and L-beam models, respectively, following the dimensions of each roof structure. The 3D model is presented in Figure 9 and Figure 10.

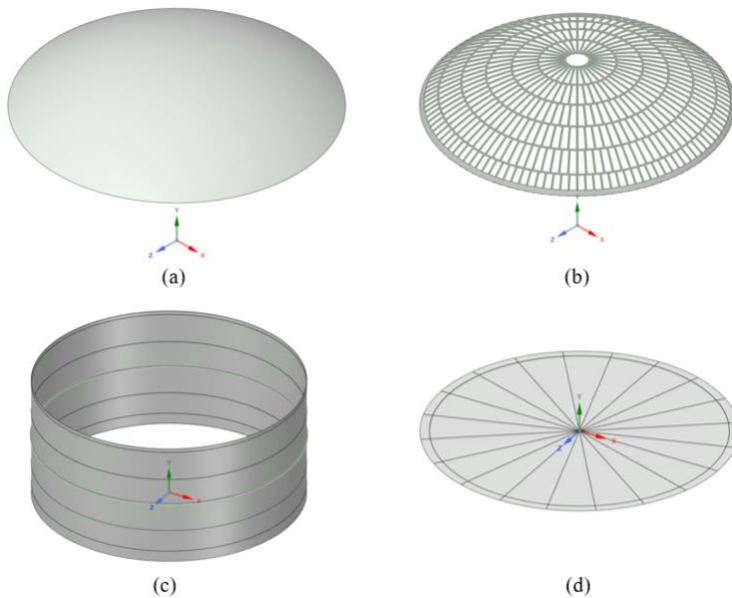


Fig. 9. 3D Model of the propane storage tank (a)roof; (b)roof structure; (c)shell; (d)bottom and annular plate.

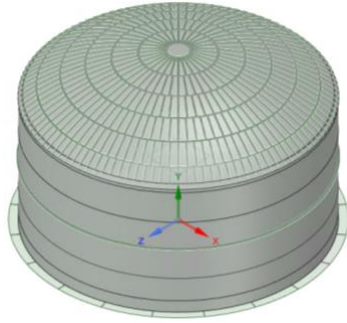


Fig. 10. 3D Model of the propane storage tank

3.2 Numerical Simulation

Using elastic-plastic analysis, several parameters must be configured beforehand for the finite element simulation. These parameters are crucial in determining the accuracy of the simulation results.

In the ANSYS Workbench finite element simulation, the parameters include component connection contact, meshing size, loading conditions, and analysis settings. The chosen contact type for the component connections was bonded, meaning the components are bound together and will not separate during the simulation.

The selected mesh size for the storage tank wall was 400 mm, as the analysis focuses on the storage wall rather than the roof or base plate structures. This mesh size complies with the meshing quality recommended by ANSYS.

The skewness value indicates that approximately 37,956 elements have a value below 0.15. The orthogonal quality Shows that around 40,070 elements have an orthogonal quality above 0.88. Based on ANSYS recommendations, the meshing quality falls into the "excellent" category. Since the meshing quality is excellent, a mesh independence study was deemed unnecessary.

Three loads were applied to the storage tank: the weight of the roof accessories, the weight of the storage tank itself, and the displacement load. The weight of the roof accessories was applied by distributing the mass over the roof to simulate the designed total weight. The weight of these accessories is approximately 300,000 kg. The weight of the storage tank was simulated using gravitational acceleration applied to all tank components. Meanwhile, the displacement load was applied to the base of the tank to simulate subsidence conditions experienced by the storage tank. The displacement values at the tank base are shown in Figure 5, which were obtained from direct field measurements at 20 different points, as depicted in Figure 6. However, the measured points do not accurately represent the actual ground settlement profile at the tank base, so the settlement values between the points around the tank's base perimeter had to be assumed.

The assumed load distribution was a linear load along the tank base perimeter. This assumption was made to prevent the storage tank's base plate from breaking or detaching during the simulation. Figure 11 visualizes this load distribution.

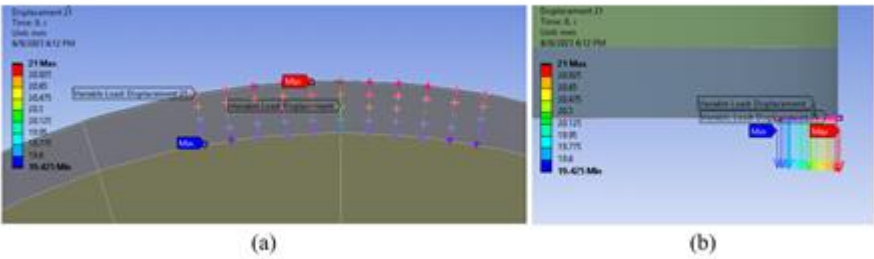


Fig. 11. Deformation load (a) bottom view, (b) elevation view

The analysis settings for the elastic-plastic simulation involved eight steps and substeps ranging from 10 to 10,000,000. Additionally, the nonlinear settings employed the Newton-Raphson iteration method and stabilization.

3.3 Simulation and Field Measurement Result Comparison

The results from the simulation with the parameters described in numerical simulation must be validated against actual measurements of the storage tank. The first validation was carried out by comparing the mass of the simulated tank with the design specifications. This comparison is presented in Table 12.

Table 12. Comparison of the simulated mass of storage tank T-201 with the design specifications

No	Component	Mass (kg)		Error
		Simulation n	Design	
1	Roof plate	248,019	256,074	3.15%
2	Roof structure	119,553	132,876	10.03%
3	Shell	744,001	747,729	0.50%
4	Bottom plate	146,540	153,510	4.54%
5	Annular plate	35,973	41,290	12.88%
6	Others (stair, nozzle, suspended deck, accessories)	300,000	300,000	0%

The simulation results generally showed lower values compared to the design, with the highest error (12.88%) occurring in the annular plate component due to assumptions made regarding the density value used. Other components exhibited minor errors, validating the tank modeling under ideal conditions before subsidence.

The measurements of the storage tank, as described in 2.1, were conducted in two orientations: 45° and 180°. These measurements serve as references for the simulation

results. Using the parameters outlined in 3.3.1, the simulation results and a comparison to the measurements in the 45° and 180° orientations are shown in Figure 12, Figure 13, Table 13, and Table 14.

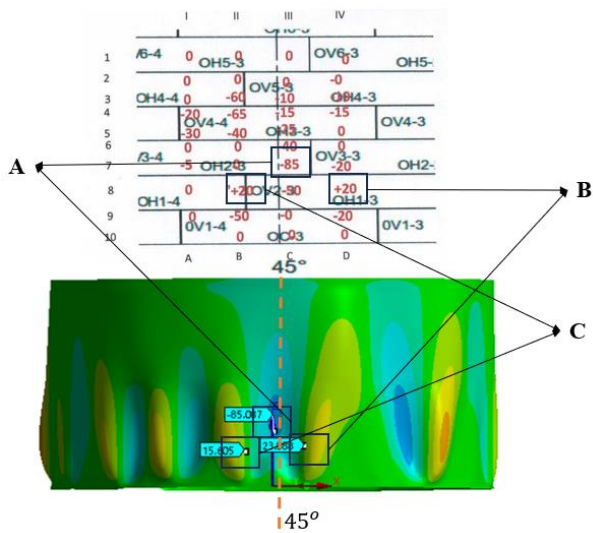


Fig. 12. Comparison of deformation values from the simulation with measurements using the string line method at the 45° orientation.

The storage tank simulation under subsidence conditions was compared at three points along the 45° orientation. In this orientation, no 3D scanning data was available, preventing visualization of the actual deformation contours. Table 13 presents the comparison of the simulation and measurement data using the string line method.

Table 13. Error values of deformation results from the simulation compared to measurements using the string line method at the 45° orientation

45° Position				
Position	Shell Course	Deformation (mm)		Error
		Simulation	String line	String line
A	3	-85.08	-85.0	0.1%
B	2	23.89	20.0	19%
C	2	15.6	20.0	22%

The errors observed in this orientation were 0.1%, 19%, and 22%. The magnitude and direction of maximum deformation in the 45° orientation are consistent with the measurements.

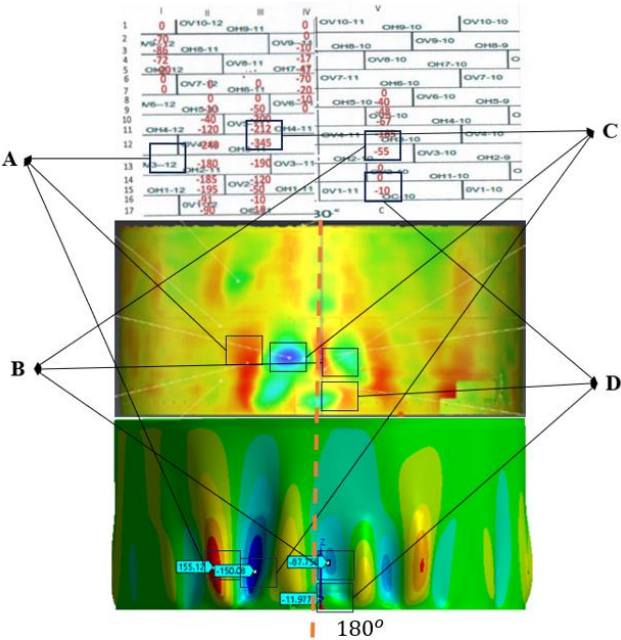


Fig. 13. Comparison of deformation values from the simulation with measurements using the string line method and the 3D scanning method at the 180° orientation

The simulation results for the storage tank under subsidence in the 180° orientation exhibited deformation contours similar to those obtained from the 3D scanning data. At position A, the red contour indicates positive radial deformation, while position C shows a blue contour, representing negative radial deformation. This suggests that the applied load assumptions align with the subsidence observed in the storage tank. However, position C revealed a concentrated deformation pattern localized in that area, unlike the broader distribution seen in the simulation. This pattern may indicate imperfections in construction or the material of the tank walls.

Table 14. Error-values of deformation results from the simulation compared to measurements using the string line method and the 3D scanning method at the 180° orientation

180° Position							
Position	Shell Course	Height (m)	Deformation (mm)			Error	
			Simulation	String line	3D Scanning	String line	3D Scanning
A	3	7.78	155.12	-	103	-	50.60%
B	3	6.93	-87.76	-55	-85	59.56%	3.24%
C	4	8.72	-150.08	-345	-309	56.50%	51.43%
D	1	4.59	-11.98	-10.0	-10	19.77%	19.77%

At the 180° orientation, four points were compared between the simulation results and the measurements using the string line method and 3D scanning. The comparison data is shown in Table 14. The maximum values from the simulation and measurements at position C differed significantly, with errors exceeding 50%. This discrepancy suggests imperfections in the storage tank, potentially related to material composition, geometric dimensions, or welding defects, particularly at position C, as discussed earlier. The height of position C is 8.727 meters, precisely at the joint between shell courses 3 and 4, where welding defects may have occurred. This warrants direct inspection to confirm any defects at the joint, as they could pose serious risks if not addressed.

Moreover, the storage tank is suspected to have experienced subsidence before the hydrostatic test, although the exact values were not recorded. This implies that the tank may have already been in a less-than-ideal condition before testing. The ANSYS Workbench simulation modeled the tank geometrically and materially perfectly. The joints between shell courses were modeled as bonded rather than welded, as described in 3.3.1. Additionally, the tank base did not undergo subsidence before the hydrostatic test in the simulation. These factors contributed to the significant differences observed in certain areas.

The deformation errors in both the 45° and 180° orientations varied widely, likely due to imperfections in the tank. The differences were also influenced by the load assumptions made during the simulation. However, the deformation contours from the simulation and 3D scanning were generally similar. Despite the high errors at specific points, the simulation results can be validated against the measurements through the string line and 3D scanning methods.

3.4 Investigation

The simulation results indicated that the maximum stress and strain occurred in shell course one at the 180° orientation. These values exceeded the yield stress of the shell course one material, A516 Gr—60N+S5, which is 334 MPa. The maximum stress and strain in the storage tank are shown in Figure 14.

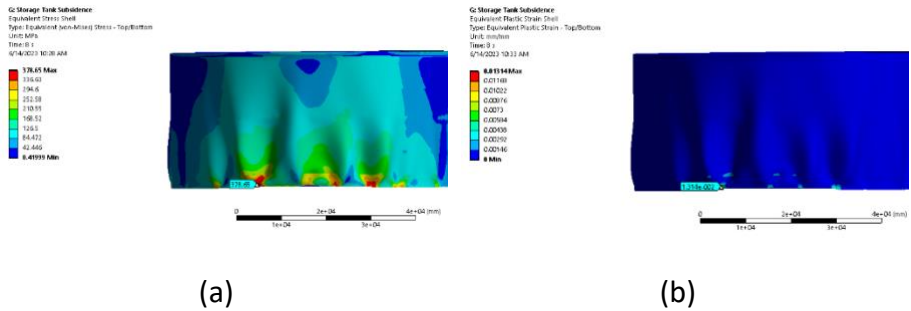


Fig. 14. Maximum value occurring in the storage tank, (a)stress, (b)strain

The simulation revealed a maximum plastic stress and strain of 378.65 MPa and 1.314%, respectively, at the 180° orientation. The stress exceeded the yield strength of the A516 Gr—60N+S5 material by 13.4%. Additionally, stress and strain values were checked at a point showing signs of defects at the junction of shell courses 3 and 4, Figure 15 illustrate this junction's stress and strain.

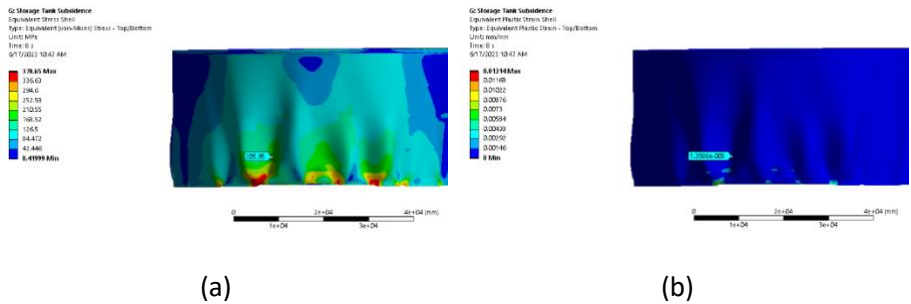


Fig. 15. Value at the joint between shell courses 3 and 4, (a)stress, (b)strain

The simulation showed that the stress and strain at shell courses 3 and 4 junctions reached 205.95 MPa. This stress value remains within the elastic region, as it does not exceed the yield strength of the A283C material used for shell courses 3 and 4. The strain also remains below the 0.2% offset strain. Due to differences between the measured and simulated values, these values do not fully represent the measurement results from the string line and 3D scanning methods. Additionally, defects at the weld

joints between shell courses 3 and 4, which could not be accounted for in the simulation, were indicated. Therefore, the analysis excluded the junction between shell courses 3 and 4, as the material remained in the elastic region.

The stress and strain observed in shell course 1 indicate that, due to the material's plastic behavior, the tank's condition cannot be analyzed using a linear method but must instead use a nonlinear approach.

The first criterion to be evaluated is protection against plastic collapse. This is assessed using a nonlinear elastic-plastic analysis with nonlinear material properties. The tank was subjected to a combination of loads, with parameters shown in Table 15.

Table 15. Parameter values for the global combined load criteria

Parameter	Value	Remark
β	26,136	3,3RSF _a
P	0	It is assumed that there are no external, internal, and hydrostatic pressures.
P _s	0	
D	D	Gravitational load is applied
T	T	Subsidence load is applied
L	0	No live load
S _s	0	No snow load

These parameters yielded a combined load factor of 2.6136(D+T). This factor indicates that the simulation should be conducted by applying gravitational acceleration and subsidence values 2.6136 times larger than the previous values. The simulation results with the combined load are shown in Fig.16, which present the plastic stress and strain.

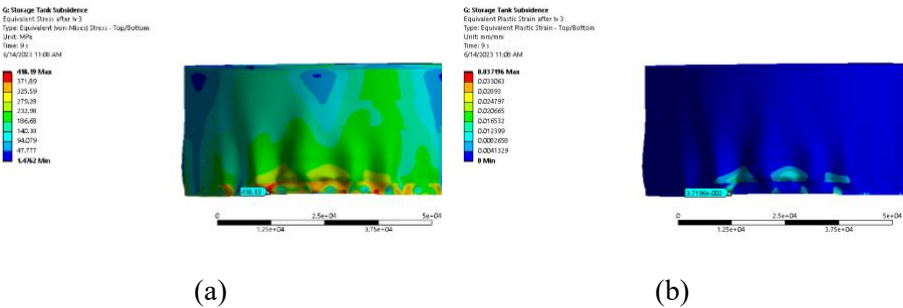


Fig. 16. Maximum values in first shell course at 180° orientation after applying combined load, (a) von Mises stress, (b) plastic strain

The storage tank simulation reached convergence. The maximum stress occurred in shell course 1, with a maximum stress value of 418.19 MPa and a maximum strain value of 0.037196 mm/mm. These stress and strain values increased after the subsidence load was applied. This is expected because the load is 2.6136 times greater than the actual load on the storage tank. The simulation results indicate that convergence was achieved when the storage tank was subjected to the combined load after subsidence. Thus, it can be concluded that the storage tank remains stable against plastic collapse under subsidence conditions.

The following criterion is protection against local failure. This is evaluated using a nonlinear elastic-plastic analysis by comparing the strain observed in the simulation to the strain during cold forming, representing the maximum allowable strain. The variable values are provided in Table 16.

Table 16. Variables for the calculation

Variable	Value	Remark
ϵ_{LU}	0.54 mm/mm	ASME BPVC Section VIII, Division 2, Table 5.7 [21]
α_{sl}	2.2	
m_2	0.1789	
σ_1	3.501 MPa	Shown in Figure 4.22
σ_2	0.0184 MPa	Shown in Figure 4.23
σ_3	416.44 MPa	Shown in Figure 4.24
σ_e	418.19 MPa	Shown in Figure 4.20

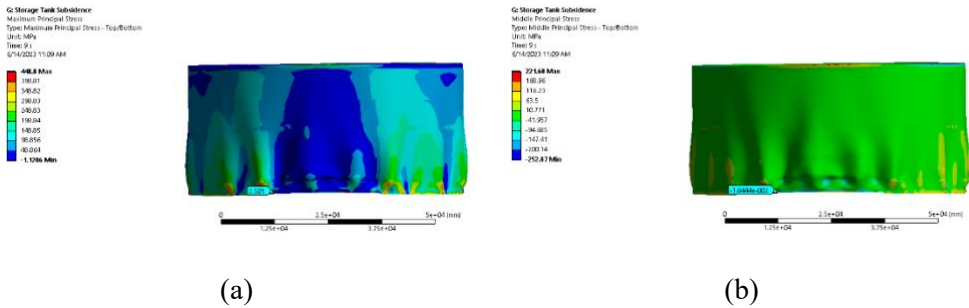


Fig. 17. Values at the point experiencing maximum von Mises stress, (a)first principle stress, (b)second principle stress

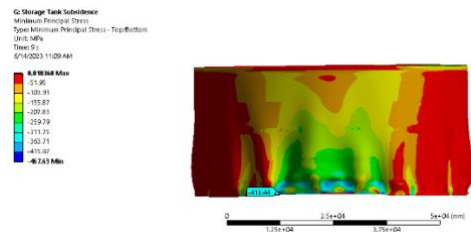


Fig. 18. The third principal stress at the point experiencing maximum von Mises stress.

Using the variables in Table 16, the value of ϵ_L is calculated to be 0.1544 mm/mm. The variables are shown in Table 17.

Table 17. Variables for the calculation of Equation 2.3

Variable	Value	Remark
T	16 mm	-
R _f	64028,2 mm	-
R _o	∞	-

Using the variables in Table 4.6, the value of ϵ_{cf} is calculated to be 0.01249 mm/mm. The value of ϵ_{peq} , representing the maximum strain obtained from the simulation, is 0.037196 mm/mm, as shown in Figure 16. The acceptance calculation is presented in Table 18.

Table 18. Acceptance calculation for local failure protection criteria

Parameter		Remark
$\epsilon_{peq} + \epsilon_{cf}$	ϵ_L	
0,0497	0,1514	$\epsilon_{peq} + \epsilon_{cf} \leq \epsilon_L$

With the acceptance criterion for local failure satisfied, the storage tank is stable and safe from local failure.

The final criterion evaluated is protection against collapse from buckling. ASME VIII Section 2, Part 5, specifies that buckling analysis is required when the storage tank is subjected to axial compressive or external loads, such as wind. In the case of the storage tank being analyzed, only subsidence loads were applied. Therefore, it was unnecessary to simulate with additional compressive or wind loads. The evaluation for protection against buckling collapse has been considered and is relevant to the protection against plastic collapse criterion, as no other external loads are assumed. Since the storage tank has been deemed safe from plastic collapse, it is also considered safe and stable against collapse due to buckling.

4 Conclusion

The conclusions that can be drawn from the operational feasibility analysis of the propane storage tank due to subsidence conditions are as follows:

The propane storage tank T-201, which has experienced subsidence and was analyzed using the fitness-for-service Level 1 method, is deemed unfit for failure in the out-of-roundness category, with a deviation result of 853 mm or 1.33%, exceeding the acceptance criteria set by the standard (300 mm or 1%). However, the propane storage tank T-201 is deemed fit for failure in the out-of-plumbness category, with a deviation result of 41.99 mm, which remains within the acceptance criteria set by the standard (150.5 mm). Both values are presented in Table 3.

The propane storage tank T-201, which has experienced subsidence and was analyzed using the fitness-for-service Level 2 method, is deemed fit for failure in the out-of-roundness category, as all remaining strength factor values are above the allowable remaining strength factor (0.9), as indicated in Table 11. Failure in the bulge category could not be determined using the fitness-for-service Level 2 method.

The propane storage tank T-201, which has experienced subsidence and was analyzed using the fitness-for-service Level 3 method, is deemed fit based on calculations where the criteria for protection against plastic collapse, local failure, and collapse due to buckling are met, as outlined in Level 3 Investigation.

The outer wall of the propane storage tank T-201 is reinforced with a stiffener plate designed based on the stresses permitted in API 620 due to the out-of-roundness failure. Additionally, due to the distortion observed in the tank wall, the tank must be monitored through regular inspections and measurements.

5 Competing Interests

The research leading to these results received funding from PT. Wijaya Karya (Persero) Tbk. under Grant Agreement No. SK/ENG-EPC/XII-2025/015A

References

1. R. Amorin, E. Broni-Bediako, D. Worlanyo, and S. A. Konadu, "The Use of Liquefied Petroleum Gas (LPG) as a Fuel for Commercial Vehicles in Ghana: A Case Study at Tema Community 1," *Curr. J. Appl. Sci. Technol.*, vol. 29, no. 2, pp. 1–8, Sep. 2018, doi: 10.9734/cjast/2018/41531.
2. X. Liu, Z. Yan, Z. Li, J. Chen, and J. Liu, "The Wind Loading Characteristics of MAN Type Dry Gas Storage Tank," *Adv. Civ. Eng.*, vol. 2020, no. 1, 2020, doi: 10.1155/2020/4974082.
3. J. M. Spritzer and S. Guzey, "Review of API 650 Annex E: Design of Large Steel Welded Aboveground Storage Tanks Excited by Seismic Loads," *Thin-Walled Struct.*, vol. 112, pp. 41–65, Mar. 2017, doi: 10.1016/j.tws.2016.11.013.
4. S. Sutjipto, "An Overview of Design Response Spectra in the Indonesian Seismic Code-SNI 1726:2012," *Puskim*, 2011.
http://puskim.pu.go.id/Aplikasi/desain_spektra_indonesia_2011/.

5. E. P. Amador, *Origin, Development, and Jurisdiction of the ASME Code History of the ASME Code*. McGraw Hill, 2004.
6. O. R. Jaiswal, D. C. Rai, and S. K. Jain, "Review of Seismic Codes on Liquid-Containing Tanks," *Earthq. Spectra*, vol. 23, no. 1, pp. 239–260, 2007, doi: 10.1193/1.2428341.
7. M. Djermane, D. Zaoui, B. Labbaci, and F. Hammadi, "Dynamic Buckling of Steel Tanks Under Seismic Excitation: Numerical Evaluation of Code Provisions," *Eng. Struct.*, vol. 70, pp. 181–196, Jul. 2014, doi: 10.1016/j.engstruct.2014.03.037.
8. C. Maraveas and K. Miamis, "Shell Buckling Evaluation of Thin-Walled Steel Tanks Filled at Low Liquid Level According to Current Design Codes," 2013.
9. W. Sengara, I. D. Sidi, A. Mulia, M. Asrurifak, D. Hutabarat, and W. Partono, "New 2019 Risk-Targeted Ground Motions for Spectral Design Criteria in Indonesian Seismic Building Code," 2019, doi: 10.1051/e3sconf/20201560.
10. American Petroleum Institute, "Welded Tanks for Oil Storage," Washington DC, 2019.
11. T. L. Anderson and D. A. Osage, "API 579: a comprehensive fitness-for-service guide," *Int. J. Press. Vessel. Pip.*, vol. 77, no. 14–15, pp. 953–963, 2000.
12. Y. Zhao, X. Lei, Z. Wang, and Q. S. Cao, "Buckling Behavior of Floating-Roof Steel Tanks Under Measured Differential Settlement," *Thin-Walled Struct.*, vol. 70, pp. 70–80, 2013, doi: 10.1016/j.tws.2013.04.015.
13. E. Hotala and R. Ignatowicz, "Effect of Settlement of Foundations on the Failure Risk of the Bottom of Cylindrical Steel Vertical Tanks for Liquids," *Stud. Geotech. Mech.*, 2019, doi: 10.2478/sgem-2019-0017.
14. J. . Teng and J. M. Rotter, *Buckling of Thin Metal Shells*. London: CRC Press, 2004.
15. A. Jäger-Cañás and H. Pasternak, "On the Axial Buckling of Very Thin-Walled Cylindrical Shells," in *Proceedings of Eurosteel 2017*, 2017, pp. 868–877.
16. J. C. Virella, L. A. Godoy, and L. E. Suárez, "Dynamic Buckling of Anchored Steel Tanks Subjected to Horizontal Earthquake Excitation," *J. Constr. Steel Res.*, vol. 62, no. 6, pp. 521–531, Jun. 2006, doi: 10.1016/j.jcsr.2005.10.001.
17. Y. Bai and X. Lin, "Numerical Simulation on Seismic Collapse of Thin-Walled Steel Moment Frames Considering Post Local Buckling Behavior," *Thin-Walled Struct.*, vol. 94, pp. 424–434, Sep. 2015, doi: 10.1016/j.tws.2015.04.033.
18. M. Stein and J. M. Housner, "Application of a Trigonometric Finite Difference Procedure to Numerical Analysis of Compressive and Shear Buckling of Orthotropic Panels," *Comput. Struct.*, vol. 9, no. 1, pp. 17–25, 1978.
19. H. Morita *et al.*, "Investigation on Buckling Behavior of Cylindrical Liquid Storage Tanks Under Seismic Excitation: 2nd Report — Investigation on the Nonlinear Ovaling Vibration at the Upper Wall," in *ASME 2003 Pressure Vessels and Piping Conference*, 2003, pp. 227–234, [Online]. Available: <http://www.asme.org/about-asme/terms-of-use>.
20. "API STD 620:2021-09 Design and Construction of Large, Welded, Low-pressure Storage Tanks." p. 332, 2019.
21. American Society of Mechanical Engineers, *Boiler and Pressure Vessel Code, Section VIII, Division 2: Alternative Rules*, Table 5.7, New York, NY, 2021.

Open Access This chapter is licensed under the terms of the Creative Commons Attribution-NonCommercial 4.0 International License (<http://creativecommons.org/licenses/by-nc/4.0/>), which permits any noncommercial use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

