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ANALYSIS OF THE STRUCTURAL INTEGRITY OF A FUEL TANK DUE TO BUCKLING USING THE FINITE ELEMENT METHOD

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Abstract
Storage tanks for fuel oil are commonly used in the oil, gas, and petrochemical industries. These tanks typically have thin-walled structures that are susceptible to buckling under excessive pressure. A hydrostatic test is required to determine the structural strength of the tank and to check for any leaks or cracks in the shell course. During the hydrostatic test, special attention must be given to the dewatering process to avoid excessive pressure differences inside and outside the tank that could lead to buckling. In this study, the tank experienced buckling in the shell course due to errors during the dewatering process, resulting in out-of-roundness in the affected shell course that exceeded the API 650 standard, with a maximum deviation of ±25 mm (from 45 m to <75 m). This thesis analyzes the causes of buckling in the tank shell course and provides recommendations for appropriate repairs so that the tank can be put back into service. NDT UT was carried out to ensure that the shell course thickness remains within the acceptable range, and NDT MPI was conducted to confirm the absence of discontinuities in the shell course welds. Based on the actual buckling condition observed in the field, repairs are recommended. For the buckling area, the use of temporary strong backs is suggested. This method is applied for the fit-up of horizontal and vertical joints. In addition, the installation of a stiffening ring is necessary to restore the tank roundness in compliance with API 650 standards. The material used for the stiffening ring is angle steel 100 × 90 × 7t.
Keywords: buckling, shell course, storage tank

Abstrak
Tangki penyimpanan minyak bakar umumnya digunakan dalam industri minyak, gas, dan petrokimia. Tangki-tangki ini biasanya memiliki struktur berdinding tipis yang rentan mengalami tekuk akibat tekanan berlebih. Uji hidrostatik diperlukan untuk menentukan kekuatan struktural tangki serta memeriksa adanya kebocoran atau retakan pada lapisan cangkang. Selama uji hidrostatik, perhatian khusus harus diberikan pada proses pengeringan untuk menghindari perbedaan tekanan yang berlebihan di dalam dan di luar tangki yang dapat menyebabkan tekukan. Dalam penelitian ini, tangki mengalami tekukan pada lapisan cangkang akibat kesalahan selama proses pengeringan, yang mengakibatkan ketidakbulatan pada lapisan cangkang yang terkena dampak melebihi standar API 650, dengan penyimpangan maksimum ±25 mm (dari 45 m hingga <75 m). Tesis ini menganalisis penyebab terjadinya tekukan pada lapisan cangkang tangki dan memberikan rekomendasi perbaikan yang tepat agar tangki dapat dioperasikan kembali. Uji NDT UT dilakukan untuk memastikan ketebalan lapisan cangkang tetap berada

dalam rentang yang dapat diterima, dan uji NDT MPI dilakukan untuk memastikan tidak adanya diskontinuitas pada sambungan las lapisan cangkang. Berdasarkan kondisi tekukan aktual yang diamati di lapangan, perbaikan direkomendasikan. Untuk area yang mengalami buckling, disarankan penggunaan penyangga sementara yang kuat. Metode ini diterapkan untuk penyambungan sambungan horizontal dan vertikal. Selain itu, pemasangan cincin pengaku diperlukan untuk memulihkan kebulatan tangki sesuai dengan standar API 650. Bahan yang digunakan untuk cincin pengaku adalah baja siku berukuran 100 × 90 × 7t.
Kata kunci: *buckling, lapisan cangkang, tangki penyimpanan*

INTRODUCTION

Storage tanks are a strategic piece of infrastructure that plays a vital role in various industrial sectors, particularly the oil and gas, petrochemical, and oil refining industries, as well as fuel distribution. Storage tanks not only serve as a means of storing raw materials and finished products but also play a vital role in maintaining supply chain continuity, ensuring operational stability, and safeguarding the quality of stored products from external environmental factors that could compromise their quality and economic value (API, 2020). In the modern energy industry, large-capacity storage tanks are a vital element because they function as buffer stock, enabling an optimal balance between production and distribution processes to be maintained.

Given that storage capacities can range from thousands to hundreds of thousands of cubic meters, storage tanks must be designed with extremely high safety standards. Structural failure of a tank can lead to very serious consequences, ranging from significant financial losses, environmental contamination due to fuel spills, and disruptions to industrial operations, to threats to human safety and surrounding facilities (Rotter, 2018). Therefore, the structural integrity of storage tanks is one of the key aspects that must be maintained throughout construction, testing, operation, and maintenance.

Most above-ground fuel storage tanks utilize a vertical cylindrical steel construction composed of several layers of circular steel plates known as shell courses. This structure falls into the category of thin-walled cylindrical shells because it has a very high diameter-to-wall-thickness ratio (Teng & Rotter, 2004). Mechanically, this thin-walled cylindrical shape is highly efficient at withstanding internal pressure generated by the stored fluid. However, this structure has an inherent weakness in the form of susceptibility to external compressive loads, which can lead to elastic instability or buckling (Brush & Almroth, 1975).

Buckling is one of the most dangerous forms of structural failure because it can occur suddenly without being preceded by significant plastic deformation. In thin-walled cylindrical structures, buckling can occur when the compressive stress acting on the tank wall reaches a certain critical value, causing drastic and permanent geometric changes (Timoshenko & Gere, 1961). Unlike failure due to material yielding, which can generally be detected through gradual deformation, buckling often occurs suddenly, making it difficult to predict through routine visual inspection alone.

In recent decades, research on buckling behavior in storage tanks has become a primary focus for researchers and structural engineering practitioners. This is due to the increasing number of tank failure cases caused by external pressure, particularly during the construction process and initial testing before the tank begins operation (Rotter, 2018). One of the stages with a high risk of buckling is the hydrostatic test.

The hydrostatic test is a mandatory procedure applied to storage tanks in accordance with international industry standards, including API 650. This test is conducted by filling the tank with water until it reaches its maximum design capacity. The primary objectives of the hydrostatic test are to verify the strength of welded joints, ensure there are no leaks in the tank structure, and evaluate the stability of the foundation under maximum load conditions (API, 2020). Through this test, various potential construction defects can be identified before the tank is put into service to store high-risk fuels.

Although the hydrostatic test aims to improve safety, this process also carries significant potential risks if not carried out according to procedure. One of the most critical phases is the water drainage process after the test is completed. At this stage, the water inside the tank is drained through the drainage system until the tank is empty again. However, if the rate of water drainage is not balanced by the inflow of air through an adequate ventilation system, the internal pressure inside the tank can drop significantly below external atmospheric pressure (Myers, 1997).

This pressure difference creates a partial vacuum, causing the tank walls to be subjected to high external pressure. Given that tank walls are relatively thin, this condition can trigger local or global deformation, ultimately leading to buckling. In various documented cases within the oil and gas industry, failures caused by vacuum during the dewatering process have even led to the partial collapse of tank structures, necessitating major repairs or the complete replacement of components (Rotter, 2018).

Damage resulting from buckling typically occurs in the upper shell course—the upper layer of the tank wall. This section usually has a thinner plate thickness compared to the lower shell course because it is subjected to lower hydrostatic pressure during normal operation. Consequently, the upper shell course becomes the most vulnerable section to deformation when external pressure occurs due to vacuum conditions (API, 2020). Such deformation can take the form of local dents, ovalization, or more complex geometric changes.

The occurrence of permanent deformation in the tank wall causes significant geometric deviations from the ideal cylindrical shape required by design standards. One of the most affected parameters is roundness—the degree to which the tank maintains its circular shape. The API 650 standard establishes specific tolerance limits for geometric deviations to ensure the tank can continue to operate safely (API, 2020). If the deviation exceeds the permitted limits, the tank's structural integrity may be compromised, and further evaluation is required.

In addition to affecting structural aspects, geometric deviations can also disrupt the operational function of the tank's internal components. In tanks using an internal floating roof, for example, wall deformation can cause disruptions in the sealing system between the floating roof and the tank wall. Imperfect contact between the seal and the wall has the potential to increase product loss due to evaporation and reduce the efficiency of the hydrocarbon emission control system (Myers, 1997).

To determine the extent of damage and formulate an appropriate repair strategy, an evaluation method is needed that can provide a comprehensive picture of the tank structure's actual condition. One widely used approach in modern industry is the combination of Non-Destructive Testing (NDT) and numerical analysis based on the Finite Element Method (FEM). NDT methods allow for the inspection of material condition without damaging the structure being tested, making them highly effective for detecting defects, cracks, or reductions in plate thickness due to corrosion or deformation (Hellier, 2013).

Ultrasonic Thickness (UT) testing is used to measure the actual thickness of steel plates and ensure that material thinning does not exceed safe limits. Meanwhile, Magnetic Particle Inspection (MPI) is used to detect surface cracks and near-surface cracks in welded joints that may arise due to stress concentration during buckling events (Hellier, 2013). The results of these two methods form the basis for determining whether the material is still serviceable or requires replacement.

On the other hand, the Finite Element Method has evolved into one of the most reliable structural analysis tools in modern engineering. FEM allows complex structures such as storage tanks to be modeled as small, interconnected elements so that the distribution of stress, strain, and displacement can be analyzed in detail (Bathe, 2006). With the help of engineering software such as SolidWorks Simulation and ANSYS, structural behavior can be predicted under various loading conditions that are difficult to replicate through field testing.

The primary advantage of FEM is its ability to identify locations of stress concentration that have the potential to become the initial points of structural failure. Additionally, this method can be used to evaluate the effectiveness of various repair alternatives before implementation in the field. Thus, the risk of failure during the repair process can be minimized, and reconstruction costs can be significantly reduced (Cook et al., 2002).

In the case of tanks that experience buckling due to vacuum during the dewatering process, some commonly applied repair methods include installing a temporary strongback to restore the tank's geometric shape and installing a stiffening ring to increase the structure's stiffness against external compressive loads. However, the effectiveness of these methods must be validated through numerical analysis to ensure that the tank's structural integrity is fully restored and meets applicable safety requirements (Rotter, 2018).

Based on the above discussion, this study focuses on analyzing a buckling case that occurred in a fuel storage tank due to external pressure during the dewatering process following a hydrostatic test. The research was conducted through a combination of non-destructive inspections, geometric evaluations based on the API 650 standard, and numerical simulations using the Finite Element Method. This approach is expected to provide a comprehensive understanding of the failure mechanisms involved and offer technical recommendations that can be applied in addressing similar cases within the industry. The research results are also expected to serve as a reference for engineers in improving the operational safety of storage tanks and reducing the risk of structural failure, which could result in significant economic and environmental impacts.

This study aims to analyze the primary causes of buckling in the shell course of fuel storage tanks resulting from external pressure during the dewatering process following a hydrostatic test. Additionally, this study aims to evaluate material integrity using non-destructive testing methods, specifically ultrasonic thickness measurement and magnetic particle inspection, to ensure there is no reduction in plate thickness or cracks in the welded joints that could compromise structural safety. This study also aims to verify the extent of the tank's geometric deviations from API 650 requirements, particularly regarding roundness tolerances in the deformed areas. Next, a numerical simulation using the Finite Element Method was conducted to analyze the distribution of stress, strain, and structural displacement under operating conditions so that the feasibility of reusing the tank could be evaluated. Ultimately, this study aims to formulate recommendations for appropriate repair methods through the use of a temporary strong back and stiffening ring and to validate the effectiveness of these methods in restoring the tank's structural integrity in accordance with applicable industry safety standards.

METHOD

This study was conducted through a series of structured stages, integrating field observations, non-destructive material testing, and computational analysis based on the finite element method (FEM). The initial stage of the study began with the identification and collection of technical data on the storage tanks owned by PT. XYZ. The collected data included the tank's primary dimensions, material specifications for each shell course, and design parameters in accordance with API 650 standards. The tank under study has an operational capacity of 50,000 m^3, with a diameter of 60,000 mm and a total height of 19,500 mm, consisting of eight shell courses.

Following a buckling incident after a hydrostatic test, a field inspection and Non-Destructive Testing (NDT) were conducted to evaluate the structure's actual condition. Visual Inspection (VI) was used to identify the locations of deformation, document the condition of the plate surfaces, and assess damage to the protective coating. Next, Ultrasonic Thickness (UT) testing was performed on the deformed areas to ensure that plate thinning did not exceed safe limits. Measurements were taken based on circumferential coordinates around the tank. Additionally, Magnetic Particle Inspection (MPI) was applied to the welded joints around the buckling area to detect potential microcracks that may have formed due to stress concentration during the deformation process.

The next step involved analyzing the geometry and roundness by measuring actual dimensions using a laser meter and a radius gauge. The measurement results were compared with the tolerances specified in API 650 to determine the degree of deviation from the tank's cylindrical shape. Subsequently, a three-dimensional model of the tank was developed using SolidWorks 2018 software and analyzed via the Finite Element Method (FEM), incorporating material parameters in accordance with ASTM standards as well as static loads in the form of operating fluid pressure. To ensure simulation accuracy, a mesh convergence study was conducted using five variations in element size until stable and representative results were obtained. Based on the results of the NDT analysis and FEM simulation, repair recommendations were formulated, including the use of a temporary strongback to restore the tank's geometric shape and the installation of stiffening rings to increase structural stiffness and ensure the tank once again meets applicable operational safety standards.

RESULTS AND DISCUSSION

Tank Specifications and Modeling

The storage tank that is the subject of the study has technical specifications designed for the storage of Pertamax/Pertalite type fuel with an operational capacity of 50,000 m3. The full technical data is shown in the table below:

PARAMETER	DESCRIPTION
CONSTRUCTION	Page 650 13th 2020
DIMENSIONS (ID X H)	60,000 mm x 19,500 mm
MAXIMUM CAPACITY	52.215 m3
DESIGN PRESSURE	Full of Water (Hydrotest)
DESIGN TEMPERATURE	80 °C
JUMLAH SHELL COURSE	8
YEAR OF DEVELOPMENT	2023

The tank wall structure uses materials with varying specifications to optimize strength and cost. The bottom and roof plates use standard carbon steel materials, while the bottom wall plates that withstand the highest hydrostatic pressure loads use steel with higher tensile strength.

SECTIONS	MATERIAL ASTM	THICKNESS (MM)
ROOF PLATE	A-283 Grade C	8
SHELL 1 (BOTTOM)	A-573 Grade 70	28
SHELL 2	A-573 Grade 70	26
SHELL 3	A-573 Grade 70	22
SHELL 4	A-573 Grade 70	18
SHELL 5	A-573 Grade 70	14

SHELL 6	A-573 Grade 70	12
SHELL 7	A-283 Grade C	10
SHELL 8 (TOP)	A-283 Grade C	8
BOTTOM PLATE	A-283 Grade C	8

UT NDT (Ultrasonic Thickness) Test Results

Plate thickness testing is performed on the *areas that are buckling* to ensure that the integrity of the plate thickness is maintained. The measurement results showed that the actual thickness still met the API 650 design criteria, which means that the deformation was not accompanied by significant material depletion that could weaken the strength of the structure locally.

BUCKLING LOCATION	AFFECTED AREAS	SHELL	ACTUAL THICKNESS (MM)	SHOE MIN. API 650	STATUS
SUDUT 135°	3850 x 5600 mm	6, 7, 8	12,1 / 10,2 / 8,1	8,57 / 8,00 / 8,00	Acceptable
SUDUT 145°	2020 x 2150 mm	7, 8	10,2 / 8,2	8,00 / 8,00	Acceptable
SUDUT 155°	2925 x 5600 mm	6, 7, 8	12,1 / 10,2 / 8,1	8,57 / 8,00 / 8,00	Acceptable
SUDUT 200°	2700 x 1500 mm	6, 7	12,1 / 10,1	8,57 / 8,00	Acceptable

This result is crucial because it shows that the integrity of the base material remains good, so that geometric improvements through cold working methods or the addition of stiffeners are possible without having to replace the tank plate as a whole.

Hasil Pengujian NDT MPI (Magnetic Particle Inspection)

Weld joint examination using MPI is performed to detect cracks due to mechanical load when *buckling* occurs. Cracks in weld joints are particularly dangerous because they can be the starting point for catastrophic failure when the tank is filled with fluid.

BUCKLING LOCATION	WELDING AREA	INSPECTION	RESULTS
SUDUT 135°	Horizontal Shell Extension 6-7 & 7-8		No Indication (Acceptable)

SUDUT 145°	Horizontal 7-8 & Vertikal Shell 7	No Indication (Acceptable)
SUDUT 155°	Horizontal Shell Extension 6-7 & 7-8	No Indication (Acceptable)
SUDUT 200°	Horizontal 7-8 & Vertikal Shell 7	No Indication (Acceptable)

The absence of any indication of cracks in the weld joints throughout the affected areas of *the buckling* provides assurance that the weld structure still has sufficient ductility to withstand the deformation that has occurred.

Analysis of Causes of Buckling

An in-depth analysis of the events in the field shows that *buckling* occurs during the *dewatering* process or discharging water after the hydrostatic test is completed. The main problem lies in the pressure imbalance between the inside and outside of the tank. When water is expelled at a high flow rate while the vent valve or upper *manhole* is not opened adequately, air from the outside cannot enter quickly to fill the empty space left by the water. This creates a partial vacuum condition inside the tank.

Because the tank is designed as an atmospheric pressure vessel, its walls (specifically *the thinner shell courses* 6, 7, and 8) do not have sufficient strength to withstand external pressure from the atmosphere. The atmospheric pressure presses the wall plate inwards to exceed the critical load of *the buckling*. This failure is classified as a failure of local elastic-plastic stability on thin walls. The most affected areas are at 135° and 145° angles, which are likely to be geometrically weakest points or areas with the least internal structural support (such as *rafters*).

Buckling Dimension Measurement and API 650 Tolerance

The dimensional measurement data on the *buckling* area showed varying radius deviations. Based on the API 650 Section 7.5.3 standard, the maximum roundness tolerance for tanks with a diameter of ≥ 45 m to < 75 m is ± 25 mm.

BUCKLING LOCATION	SHELL AFFECTED	ACTUAL DEVIATION (MM)	API 650 TOLERANCE	RESULTS
SUDUT 135°	Shell 7	-35 mm	± 25 mm	Out of Tolerance
SUDUT 145°	Shell 8	-35 mm	± 25 mm	Out of Tolerance
SUDUT 155°	Shell 7	-18 mm	± 25 mm	Within Tolerance

SUDUT 200°	Shell 7	-18 mm	± 25 mm	Within Tolerance

Deviations of -35 mm at 135° and 145° angles technically indicate that the tank is in a "Not-Acceptable" condition for construction handover without any repair action. Although it is still safe in thickness, this geometric distortion can cause long-term operational problems.

FEM Numerical Simulation Analysis (Finite Element Method)

The simulation was carried out with the scenario of a tank filled with operational fluid to evaluate the strength of the remaining structure that has been deformed. The main focus is on the voltage distribution of the Von Mises.

The results of the simulation with *mesh* variations provide the following data:

MESH	STRESS MAXIMUM (PSI)	DISPLACEMENT (MM)	STRAIN MAXIMUM
MESH 1	1.660	6,17	4,88 \times 10^{-5}
MESH 2	3.810	13,90	1,18 \times 10^{-4}
MESH 3	7.510	36,20	2,02 \times 10^{-4}
MESH 4	12.400	39,40	3,96 \times 10^{-4}
MESH 5	17.800	81,70	5,17 \times 10^{-4}

A maximum voltage of 17,800 psi on the fine mesh was found concentrated in the transition area of the *shell course*. Although this value is still far below the yield *strength* limit of A-573 Grade 70 (about 42,000 psi) and A-283 Grade C (about 30,000 psi) materials, the *displacement* value of 81.7 mm on the roof indicates that the structure has overflexibility. This confirms that although the strength of the tank material does not fail (does not break), the tank has functionally lost shape stability which can interfere with the operation of *manhole doors* or automatic level measurement systems.

Recommended Repair Methods

To restore the integrity and geometry of the tank, two main technical improvement steps are recommended:

1. Use of Temporary Strong Back: This method involves installing an auxiliary device in the form of a curved steel profile (*strong back*) that is installed vertically and horizontally on the dented area. Using the help of mechanical or hydraulic jacks and a hook system (*horse shoe*), the inward bending plate is slowly pulled back to its nominal radius. This process is carried out in cold conditions without overheating to maintain the mechanical properties of the material. Once the plate is straight again, the weld joint is re-inspected with NDT to ensure there are no new cracks due to the pulling process.

2. Additional Stiffening Ring Installation: To strengthen the area that has buckled and prevent recurrence, permanent *stiffening rings* are installed . Based on the analysis, the ideal position is on *shell course* 6 as the main support of the thinner upper tank.

a. Material: Besi Siku (L) 100 mm x 90 mm x 7t.

b. Function: Increase the cross-sectional moment of the tank wall inertia against the lateral compressive load, thus raising the critical pressure value *of the overall buckling* structure.

c. Verification Results: The use of this material size has been calculated in accordance with *the Section modulus requirements* in API 650 and is declared to be able to maintain the roundness of the tank stable under operational conditions.

Mechanical Integrity Evaluation

A final review of the actual condition of the tank compared to the API 650 standard shows the following level of conformity:

PARAMETER	ACTUAL CONDITION	API 650 TERMS	STATUS
THICK ROOF	8 mm	6 mm	Conform
SHELL THICKNESS 1	28 mm	25.9 mm	Conform
SHELL THICKNESS 8	8 mm	8.0 mm	Conform
ROUNDABOUTS	Deviation -35 mm	Max ± 25 mm	Not Suitable (Needs Repair)
STIFFENING RING	L 100x90x7T	L 65x65x8T	Compliant (Exceeds Standard)

Although there are discrepancies in the roundness aspect due to *the dewatering* incident, the integrity of the thickness and quality of the material are maintained. With repairs using *strong backs* and the installation of *stiffening rings*, the tank can technically be restored to acceptable condition and safe for long-term operation

CONCLUSION

Based on the entire series of research, testing, and analysis that has been carried out on the phenomenon of *buckling* in fuel storage tanks, the following conclusions can be drawn:

1. The main cause of *buckling* in *shell courses* 6, 7, and 8 is an operational error during the *dewatering* process after hydrostatic testing. The rate of discharge of water that is out of balance with the air intake creates internal vacuum pressure that causes the thin walls of the tank to lose stability and bend inward due to external atmospheric pressure.

2. Non-destructive testing (NDT) via *Ultrasonic Thickness* confirms that the thickness of the plate in the deformed area is still above the design minimum limit (12.1 mm for *shell* 6; 10.2 mm for *shell* 7; and 8.1 mm for *shell* 8), thus maintaining the integrity of the base material.
3. Magnetic *Particle Inspection* (MPI) testing of horizontal and vertical weld joints in the *buckling* area showed no indication of cracking or discontinuity, proving that the weld joint still has adequate integrity strength.
4. The maximum radius deviation of -35 mm at 135° and 145° angles exceeds the API tolerance limit of API 650 (± 25 mm), so the tank requires geometric corrective measures to re-meet international construction standards.
5. A simulation of the Finite Element Method (FEM) shows a maximum Von Mises stress distribution of 17,800 psi, which is still below the material yield limit, indicating that the tank is structurally not experiencing rupture failure, but requires reinforcement for shape stability.

The recommended repair method is the use of *a temporary strong back* to correct the roundness of the plate and the installation *of a permanent stiffening ring* (100x90x7t elbow iron) on the *shell course* 6 to increase the rigidity of the structure and prevent *buckling* in the future operational period.

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