

## Enhancing Crude Oil Tank Inventory Stock Availability at PT Kilang Pertamina for National Fuel Security

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### ABSTRACT

In 2022, PT Kilang Pertamina International (KPI) Unit VI Balongan initiated the RDMP project to increase crude oil capacity to 150 MBSD (Million Barrels per Stream Day) by adding equipment to the CDU. However, refinery capacity growth faced challenges due to corrosion and leaks in the crude oil tank walls. Repairing these issues through welding while the tanks were onstream posed safety risks, including explosions. As an alternative, the COMPACT team implemented the FEA + Composite Patch solution, using a cold work method to minimize risk and avoid downtime. Laboratory testing confirmed that the repair increased material strength by up to 10%. Further structural analysis of tank 42-T-101B using standard fitness-for-service (FFS) procedures revealed that the tank initially failed to meet safety criteria due to metal loss. However, local defect analysis indicated that, if mitigated, the tank could meet the required standards. Proposed mitigation measures, such as reducing the maximum allowable fill height (MAFH) or adjusting the RSFa value, would ensure compliance. Composite patch repairs also showed significant improvements in the tank's ability to withstand collapse, extending its lifespan by up to 62 years, supporting the continued safe operation of the storage tank and contributing to national fuel security.

**Keywords:** Stock Availability Optimization, Compact Solution for Inventory Management, National Energy Security of Supply.

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### INTRODUCTION

Indonesia's growing energy demands require a robust and reliable infrastructure to ensure the continuous availability of fuel for domestic consumption and industrial activities (Rahman et al., 2021). As the nation's energy needs expand, the role of efficient crude oil storage and management becomes increasingly significant in supporting energy security and economic stability (Le & Nguyen, 2019). Refineries and storage facilities serve as critical components in the energy supply chain, enabling the safe and efficient handling of crude oil inventories (Lima et al.,

2016). However, maintaining the structural integrity and operational readiness of these facilities presents both technical and logistical challenges that demand strategic planning and innovative solutions (Wang, 2016).

PT Kilang Pertamina (PT KPI) plays a crucial role in ensuring the supply of fuel for Indonesia's national energy needs. As part of its strategic efforts to maintain energy security, the company continuously works to enhance its refining and storage capabilities (Anggraito et al., 2023). One of the key challenges is ensuring the optimal availability of crude oil tank inventories to meet the growing demand for fuel (Panda & Ramteke, 2019). In this regard, PT KPI's focus has been on improving stock management systems and boosting tank storage capacity, particularly at critical facilities such as the Balongan Refinery (Unit VI). These efforts are vital to maintain a steady supply of fuel and avoid any disruptions that could affect the national economy (Milza & Rahadi, 2023).

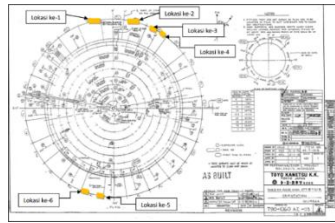
The improvement of crude oil tank inventory stock availability is essential for safeguarding Indonesia's energy security. Given the dynamic nature of crude oil supply chains, factors such as fluctuations in production, geopolitical uncertainties, and unexpected disruptions can pose risks to the national fuel supply (Dahri & Siallagan, n.d.). To address these challenges, PT KPI is implementing innovative solutions to optimize stock management and enhance storage efficiency. This approach not only ensures sufficient stock availability but also supports the company's long-term goal of achieving energy self-sufficiency and securing a stable, uninterrupted fuel supply for the country (Irzanova, 2023).

Hoarding Tank Tag No 42-T-101B, built and operated in 1993 by PT Pertamina International Refinery RU VI Balongan with a maximum storage capacity of 67000 m<sup>3</sup>. In mid-2023 PT Kilang Pertamina Internasional inspected the tank and reported 6 defects in the course-1 section, and one defect in the course-5 section. To see the impact of the defects found, PT Kilang Pertamina Internasional RU VI Balongan wants to conduct an engineering study on the operational feasibility of the Hoarding Tank (Azhari & Salsabila, 2023).

Previous research conducted by (Ali et al., 2020) stated that the demand for inventory in this study is modeled using Poisson distribution, considering constant lead times, and applies the (Q, r) model with stock-out cost and backorder cost approaches. Both approaches lead to improved service levels and reduced average inventory investment, with the stock-out cost approach achieving an 8.88% increase in service level and a 56.9% reduction in inventory investment, while the backorder cost approach shows a 7.77% improvement in service level and a 57% decrease in inventory investment. These results positively impact plant uptime, productivity, and reduced maintenance costs by efficiently managing maintenance stock, which can be applied to various industries, including oil and gas.

This Fitness for Service (FFS) study work is intended to analyze the feasibility of Tank 42-T-101B against the liquid level limitation of Tank 42-T-101B. The study of liquid level limitation is important because it will have an impact on reducing the company's business performance. To

determine the feasibility of the stockpile tank based on applicable standards, a more detailed and comprehensive evaluation of the tank condition based on the actual condition of the tank is required.



(a)



(b)



(c)

**Figure 1. Location (a&b) of course-1 and (c) Visual condition of course-5 corrosion on tank 42-T-101B [B.1][B.2]**

Job Purpose:

1. Conduct FFS Level 1, 2, and 3 assessments on storage tank 42-T-101B.
2. Provide recommendations based on the results of FFS Level 1, 2, and 3 assessments on storage tank 42-T-101B.

The urgency of this research stems from the critical role that crude oil storage tanks, such as 42-T-101B, play in maintaining national fuel security. Any failure or operational inefficiency in these storage tanks could disrupt fuel supply, which would have far-reaching economic and social consequences. By conducting FFS assessments, potential risks can be identified early, ensuring that necessary interventions are made promptly to avoid unscheduled downtime, thus guaranteeing a stable and secure supply of fuel for the nation.

Based on the outlined objectives and benefits, this study aims to comprehensively evaluate the current condition and structural integrity of storage tank 42-T-101B through Fitness-for-Service (FFS) assessments at Levels 1, 2, and 3. By identifying potential risks and providing evidence-based recommendations, the research seeks to enhance the tank's operational reliability and safety, ensuring its readiness for continued crude oil storage. Additionally, the findings will support PT Kilang Pertamina in optimizing its storage infrastructure, contributing to improved operational efficiency, cost savings, and national fuel security. This research underscores the critical role of proactive maintenance and strategic management in safeguarding Indonesia's energy resilience.

## RESEARCH METHOD

This research is an applied research that aims to conduct a defect feasibility study on storage tank 42-T-101B using API 653 and API 579 standards as the main guide in evaluating the degradation of existing defects. The data analysis techniques used include visual inspection to identify defects, Fitness-for-Service (FFS) assessment using Level 1, 2, and 3 methods from API 579, and quantitative risk analysis (QRA) to assess the potential impact of defects on tank performance. Data collection techniques include on-site inspection, non-destructive testing (NDT) such as ultrasonic, radiographic, and magnetic particle testing, and review of historical data such as maintenance records and previous inspection reports. The main data sources are from API 653 and API 579 standards, tank maintenance records, inspection results, as well as relevant industry guidelines. This research aims to provide data-driven recommendations to ensure tank structural integrity and support optimal crude oil stock availability at PT Pertamina Refinery to maintain national energy security.

## RESULT AND DISCUSSION

### RESULT

#### FFS Level 1 & 2

FFS level 1, 2, and 3 calculations were performed to review the damaged stockpile tanks. Figure 5 1 shows the steps involved in performing FFS level 1, 2, and 3 calculations.

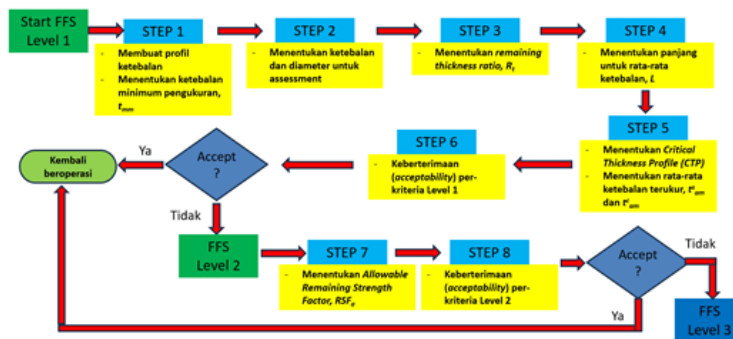


Figure 2. Flowchart of FFS in the case of metal loss

The FFS analysis was conducted using the Part 4: Assessment of General Metal Loss (API 579-1/ASME FFS-1) standard. Thus, to maintain the conservativeness of the results, the assessment was conducted using Part 4. In addition, API 579-1/ASME FFS-1 also recommends performing calculations on Part 4 before going to Part 5 (API 579-1/ASME FFS-1, Paragraph 5.1.2).

#### Level 1 and Level 2 FFS Results

A summary of the FFS Level 1 and 2 results can be seen in table 1 as follows:

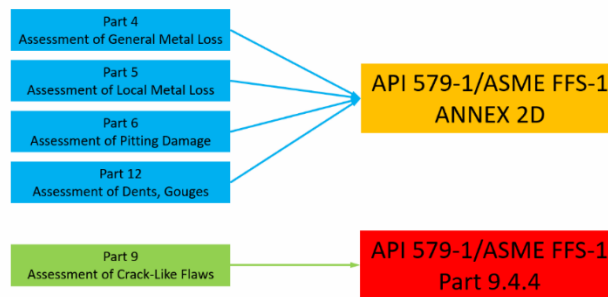
**Table 1. Summary of FFS Level 1 and 2 results**

Metal loss	MSD Check	Level 1			Level 2			Location
		MFHr (m)	MFH Assessment	Minimum Measured Thickness Check	MFHr (m)	MFH Assessment	Minimum Measured Thickness Check	
#1	UNACCEPTABLE	15.1	ACCEPTABLE	ACCEPTABLE	16.74	ACCEPTABLE	ACCEPTABLE	Shell#1 350°
#2	UNACCEPTABLE	15.1	ACCEPTABLE	ACCEPTABLE	16.74	ACCEPTABLE	ACCEPTABLE	Shell#1 10°
#3	UNACCEPTABLE	15.09	ACCEPTABLE	ACCEPTABLE	16.73	ACCEPTABLE	ACCEPTABLE	Shell#1 20°
#4	UNACCEPTABLE	15.09	ACCEPTABLE	ACCEPTABLE	16.73	ACCEPTABLE	ACCEPTABLE	Shell#1 35°
#5	UNACCEPTABLE	15.1	ACCEPTABLE	ACCEPTABLE	16.74	ACCEPTABLE	ACCEPTABLE	Shell#1 190°
#6	UNACCEPTABLE	15.1	ACCEPTABLE	ACCEPTABLE	16.74	ACCEPTABLE	ACCEPTABLE	Shell#1 200°
#7	UNACCEPTABLE	15.12	ACCEPTABLE	ACCEPTABLE	15.62	ACCEPTABLE	ACCEPTABLE	Shell#5 240°

**FFS Level 3**

**Introduction**

The FFS Level 3 assessment procedure refers to ANNEX 2D in API 579-1/ASME FFS-1 Fitness for Service. In ANNEX 2D of API 579-1/ASME FFS-1 Fitness for Service, all detailed stress analysis procedures refer to ASME B&PV Code Section VIII, Division 2 (VIII-2), Part 5: Design by Analysis. The assessment method in this ANNEX is based on the results of stress analysis using numerical analysis.



**Figure 3. FFS Level 3 assessment procedure**

The procedures in this ANNEX are designed to evaluate defective components against several failure modes, including:

- a. Protection Against Plastic Collapse (2D.2)
- b. Protection Against Local Failure (2D.3)
- c. Protection Against Collapse from Buckling (2D.4)
- d. Protection Against Fatigue Damage (Part 14)

For the FFS Level 3 assessment, the Protection Against Plastic Collapse method was chosen: Elastic-Plastic Stress Analysis Method and Protection Against Local Failure: Elastic-Plastic Analysis. Both methods were chosen because they can simulate the plastic condition of the

material, making it closer to the actual material condition. It is different if only using the elastic condition of the material, because it will be less close to the actual condition of the material. Determination of acceptance criteria for each method uses the following logic:

1. Protection Against Plastic Collapse: Elastic-Plastic Stress Analysis Method

$$\text{If, } P_{design} \beta < P_{collapse} \Rightarrow \text{ACCEPTABLE}$$

2. Protection Against Local Failure: Elastic-Plastic Analysis

$$\text{If, } \varepsilon_{peq} + \varepsilon_{cf} \leq \varepsilon_L \Rightarrow \text{ACCEPTABLE}$$

**Material Model**

The material model is used as input to the finite element software with its mechanical properties. Table 2 is the mechanical properties inputted in the modeling of tank 42-T-101B.

**Table 2. Properties (mechanical properties) of materials**

Materials	Density (ton/mm) <sup>3</sup>	E (MPa)	v	YS (MPa)	UTS (MPa)	Application	Reference
A-105	7.80E-09	190000	0.29	250	485	Pipe N1, N2, N6, N7AB, N7CD, N8, N9	ASME BPVC 2021 Section II Part A-1
A-283 C	7.80E-09	200000	0.29	205	380	Tank bottom, Shell-5, Shell-6	ASME BPVC 2021 Section II Part A-1
A-573 70	7.80E-09	200000	0.29	290	485	Shell-1, Shell-2, Shell-3, Shell-4, Pad, M1, N4, Reinforcement Pad, Annular plate	ASTM A-573
SS41	7.80E-09	200000	0.29	245	400	Bracket	<a href="https://www.theworldmaterial.com/jis-g3101-ss400-steel-equivalent-material/">https://www.theworldmaterial.com/jis-g3101-ss400-steel-equivalent-material/</a>
Rockwool	1.92E-10	-	-	-	-	Insulation	Weekly progress 01 discussion

**Model Geometry**

1) Course Shell Model

Geometry modeling is done using CAD software as a prefix to create the three-dimensional shape of Tank 42-T-101B. In general, the geometry of the tank model uses dimensions such as Table 3.

**Table 3. Summary of tank model geometry dimensions 42-T-101B**

Description	Value	Unit
Shell ID	84600	mm
Area of inside shell	5.62E+09	mm <sup>2</sup>
Shell Height	15500	mm
Number of shell courses	6	-
Shell Thickness:	26.67	mm

Description	Value	Unit
Shell#1	21.77	
Shell#2	15.78	
Shell#3	10.98	
Shell#4	9.53	
Shell#5	9.53	
Shell#6		
Shell Height:	2571	
Shell#1	2571	
Shell#2	2571	
Shell#3	2570	mm
Shell#4	2571	
Shell#5	2571	
Shell#6		

## 2) Finite Element Model

Once the geometry of the model is created, the finite element model is built by discretizing the model geometry. Figure 4 is an overview of the model that has been imported into the Abaqus software.

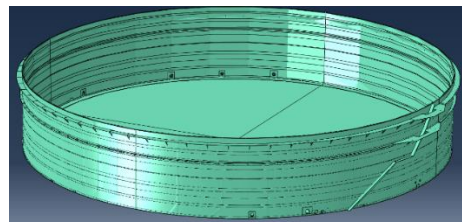


Figure 4. Overall tank model in Abaqus

### Convergence Test

Convergence tests in finite element analysis (FEA) are an important process to ensure the accuracy and reliability of simulation results (Szabó & Babuška, 2021). These convergence tests examine how the solution of an FEA model changes with modifications to the element size or mesh precision.

### **Boundary Conditions & Load Convergence Test**

An overview of the boundary conditions can be seen in Figure 5 and Figure 6.

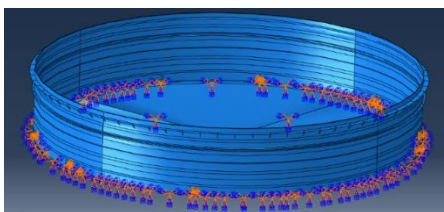


Figure 5. Boundary conditions of the bottom tank

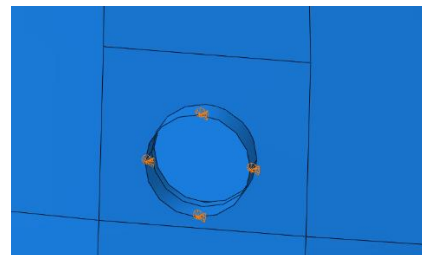


Figure 6. Boundary conditions at the nozzle

The load in the convergence test uses hydrostatic pressure at a liquid height of 13990mm as shown in Figure 7, and a gravity load to describe the dead load of the storage tank as shown in Figure 8.

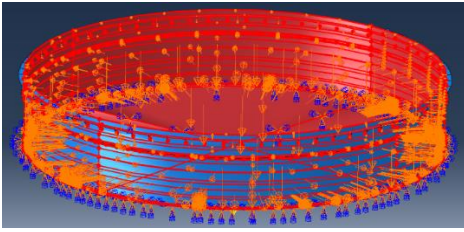


Figure 7. Load hydrostatic pressure (Liquid Height 13990 mm)

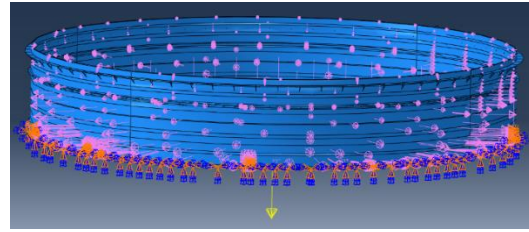


Figure 8. Load gravity (9810 mm/s<sup>2</sup>)

### Element Variations

Table 4. Variation of the number of elements

Mesh size (mm)	Element Number
500	73131
300	125583
200	244998
150	377109

Convergence Test was conducted using 4 variations of mesh accuracy, the number of elements varied from 73131 to 377109 elements. An overview of the elements in the tank can be seen in Figure 9.

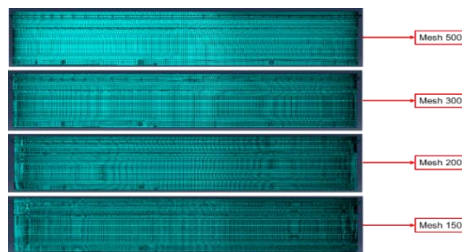


Figure 9. Visual mesh convergence test

### Convergence Test Results

The convergence test results show the maximum stress results occur in the area around Nozzle 5. This point becomes the observation parameter for the stress value for each element variation modeled.

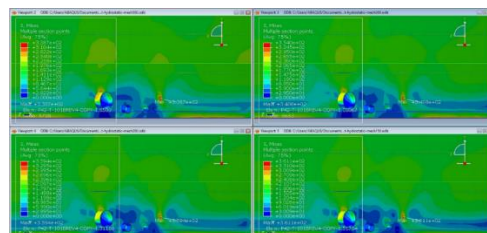
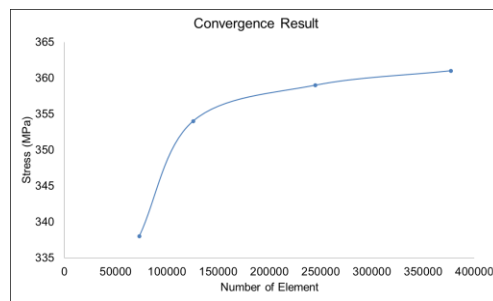


Figure 10. Convergence test result

In general, models with element sizes of 300 to 150 have differences of less than 5%. It can also be illustrated graphically that the modeling has converged and can be used as a basis for continuing the level 3 FFS analysis. In this work, the model to be used is the model with element size 200. An overview and the difference in stress values in percentage can be seen in Figure 6 and Table 5.

**Table 5. Difference in convergence test voltage results**

Mesh size (mm)	Element Number	Max Stress (MPa)	Difference
500	73131	338	-
300	125583	354	4.7%
200	244998	359	1.4%
150	377109	361	0.6%



**Figure 11. Distribution of convergence test stress values**

**Results of sensitivity analysis**

Sensitivity analysis of thickness was conducted due to some differences in thickness data from inspection results. The analysis condition is performed by giving a plastic collapse load in each scenario. The results of the sensitivity analysis are shown in Table 15.

The results of the sensitivity analysis show that the smallest LF value is found in Scenario 1, so the model with Scenario 1 configuration is used for further analysis (to maintain conservatism).

**Fitness for Service Assessment Level 3**

**Load Case**

There are 5 loading combinations in the Global Criteria in accordance with API 579 standard. In addition, Load number 3 will be ignored because the equation after the snow load is removed becomes the same as number 1 and because number 1 is more conservative. So the loading for level 3 modeling only takes Load case criteria number 1, 2, 4, and 5.

Improving Stock Availability of Crude Oil Tank Inventory Through the "Compact Solution" Method to Maintain Security of Supply of National Fuel Fuel at PT Kilang Pertamina International Unit VI Balongan

Design Conditions		
Criteria	Required Factored Load Combinations	
Global Criteria	Load Case	Load Combination
	1	$\beta(P + P_s + D)$
	2	$0.88\beta(P + P_s + D + T) + 1.13\beta L + 0.36\beta S$
	3	$0.88\beta(P + P_s + D) + 1.13\beta S + (0.71\beta L \text{ or } 0.36\beta W)$
	4	$0.88\beta(P + P_s + D) + 0.71\beta W + 0.71\beta L + 0.36\beta S$
	5	$0.88\beta(P + P_s + D) + 0.71\beta E + 0.71\beta L + 0.14\beta S$
Local Criteria	$1.7(P + P_s + D) \cdot RSF_s$	

Figure 12. Design condition elastic plastic stress analysis [A.1]

The parameters used in the load combination calculation can be seen in Table 6. Specifically for the  $\beta$  value, the value will be calculated based on the design margin and allowable Remaining Strength Factor (RSFa). In this report, the RSFa value uses a conservative value of 0.9. This RSFa value can be modified based on the equipment construction code.

Table 6. Load combination parameters RSFa 0.9

Parameters	Value	Description
$\beta$	2.25	Design Margin x RSFa
$0.88\beta$	1.98	-
$0.71\beta$	1.5975	-
$0.36\beta$	0.81	-
P (MPa)	0.1	Working pressure (atmospheric)
Ps (MPa)	0.123	Hydrostatic pressure
D (Kg)	896674	Deadload
T (°C)	65	Design Temperature
W (MPa)	0.00113364	Wind load
Liquid Level (mm)	13990	Design liquid level
E (N.mm)	6.1209E+10	Earthquake
RSFa	0.9	From FFS level 1 and 2

From the above parameters, the load values applied in the modeling can be seen in Table 18.

Table 7. Load case scenario

Criteria	Liquid Level	P	Ps	D	W	T	E	
Global Criteria	Load Case 1	100%	0.1	0.123	896674	N/A	N/A	N/A
	Load Case 2	100%	0.1	0.123	896674	N/A	65	N/A
	Load Case 4	100%	0.1	0.123	896674	0.00113	N/A	N/A
	Load Case 5	100%	0.1	0.123	896674	N/A	N/A	6.1209E+10
Local Criteria	100%	0.1	0.123	896674	N/A	N/A	N/A	

**Global Criteria Result**

In order for the tank to meet the FFS Level 3 acceptance criteria for the global failure mode, the results of the Plastic Collapse Load analysis of the tank must meet the acceptance criteria for all applicable Load Cases.

Based on the global criteria/Protection Against Plastic Collapse (PAPC), the tank with the existing defect does not meet the FFS Level 3 acceptance criteria if it is filled with product with a MAFH of 13990mm. Global Criteria results using RSFa 0.9.

**Table 8. Results of global criteria RSFa 0.9**

Criteria	Liquid Level	P	Ps	D	W	T	E	Plastic Collapse Load Factor (PCLF)	$\beta$	Allowable Load Factor (ALF)	Status	
Global Criteria	Load Case 1	100%	0.1	0.123	896674	N/A	N/A	N/A	2.109	2.25	$1 \times \beta = 2.25$	PCLF < ALF NOT PASS
	Load Case 2	100%	0.1	0.123	896674	N/A	65	N/A	2.109	2.25	$0.88 \times \beta = 1.98$	PCLF > ALF PASS
	Load Case 4	100%	0.1	0.123	896674	0.00113	N/A	N/A	2.102	2.25	$0.88 \times \beta = 1.98$	PCLF > ALF PASS
	Load Case 5	100%	0.1	0.123	896674	N/A	N/A	6.12E+10	1.893	2.25	$0.88 \times \beta = 1.98$	PCLF < ALF NOT PASS

**Local Criteria Result**

Based on the local criteria/Protection against local failure (PALF), the tank meets the FFS Level 3 acceptance criteria if it is filled with product with a MAFH of 13990mm. Table 9 shows the overall results of the local criteria.

**Table 9. Local criteria results**

Location	$\epsilon_{peq}$	$\epsilon_{Lu}$	$\alpha_{sl}$	$m_2$	$\sigma_1$	$\sigma_2$	$\sigma_3$	$\sigma_e$	$\epsilon_L$	Assessment
Metal Loss#1	2.95E-03	0.24124	2.2	0.24124	3.81E+02	1.71E+02	0.00E+00	3.31E+02	0.16256	Accept
Metal Loss#2	5.60E-03	0.24124	2.2	0.24124	4.08E+02	1.93E+02	0.00E+00	3.53E+02	0.15951	Accept
Metal Loss#3	7.42E-03	0.24124	2.2	0.24124	4.22E+02	2.03E+02	0.00E+00	3.65E+02	0.15853	Accept
Metal Loss#4	1.15E-02	0.24124	2.2	0.24124	4.46E+02	2.19E+02	0.00E+00	3.87E+02	0.15763	Accept
Metal Loss#5	3.21E-03	0.24124	2.2	0.24124	3.84E+02	1.73E+02	0.00E+00	3.34E+02	0.16213	Accept
Metal Loss#6	5.40E-03	0.24124	2.2	0.24124	4.06E+02	1.92E+02	0.00E+00	3.52E+02	0.15963	Accept
Metal Loss#7	5.17E-05	0.27632	2.2	0.27632	2.04E+02	3.80E-01	-1.60E+00	2.05E+02	0.27797	Accept

**Fitness for Service Assessment Level 3 Summary**

To meet the FFS Level 3 acceptance criteria, the acceptance criteria for all failure modes, both global (PAPC) and local (PALF) must be met. Based on the results of the FFS Level 3 assessment, the 42-T-101B storage tank with the existing defects does not meet the FFS Level 3

acceptability criteria. Note that the acceptance criteria for global and local failure modes are based on an RSFa=0.9 value, and a maximum fill height of 13990 mm.

### Defect Mitigation

#### Non-Metallic Repair

Non-metallic repair is a method of repairing a damaged/defective surface using materials that do not contain metal. Thus, non-metallic repair can be done when the equipment is in operation, this is because non-metallic repair does not require heat. Referring to ASME PCC-2 2022, the materials that can be used as non-metallic repair are composites. The repair scheme using composites based on ASME PCC-2 2022 is in Figure 13.

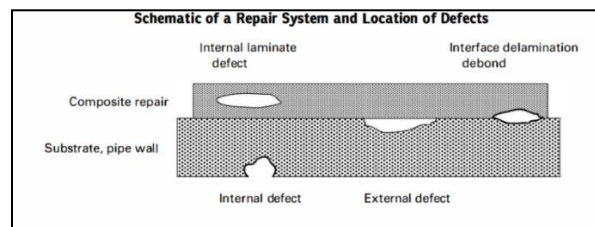


Figure 13. Non-metallic repair scheme [A.6]

From the repair scheme shown in Figure 28, the composite does not interact directly with the defect, so the defective part needs to be leveled with the surrounding surface. Based on ASME PCC-2 2022 the material for leveling the defect is called infill material. This infill material serves to pass the load from the substrate/steel to the composite. The scheme of using infill material on the defect is shown in Figure 14.



Figure 14. Schematic of defect filler material

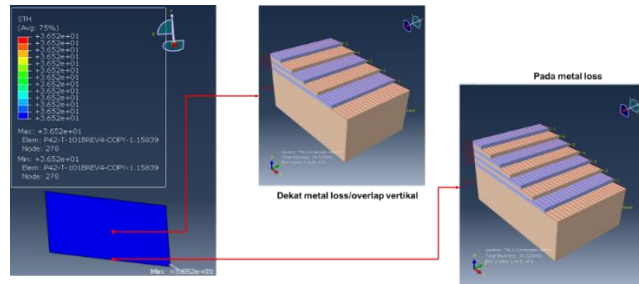
#### Non-Metallic Repair Geometry Model

The configuration of the filler material for each metal loss is shown in Table 24, the thickness of the composite to be used as a patch will be subjected to sensitivity analysis to determine the optimal thickness.

Table 10. Thickness of filling material

Location	Remaining Thickness (mm)	Target Thickness (mm)	Thickness of filling material (mm)
Metal Loss#1	25.52	26.52	1
Metal Loss#2	24.52	26.52	2
Metal Loss#3	22.52	26.52	4
Metal Loss#4	21.55	26.52	4.97
Metal Loss#5	25.52	26.52	1
Metal Loss#6	24.52	26.52	2
Metal Loss#7	7.05	9.41	2.36

The composite modeling in Abaqus software is shown in Figure 15, the part given by the composite is divided into 2, namely at the metal loss and around the metal loss. In the metal loss section, the configuration sequence is substrate/steel, filler material, and composite. While around the composite, the configuration is only substrate/steel and composite.



**Figure 15. Composite model in Abaqus software**

**Non-Metallic Repair Analysis Results**

Sensitivity analysis was performed to obtain the optimal composite configuration results. The results of the sensitivity analysis are shown in Table 11 and converted to a graph in Figure 30, the simulation conditions are at design operating conditions.

**Table 11: Results of sensitivity analysis of composite ply counts**

Number of <i>ply</i> near ML	Total <i>ply</i> thickness (mm)	Max. Stress <sup>1</sup> (MPa)	Voltage reduction <sup>2</sup>
<i>W.O Repair</i>	0	302	0
5	10	299	0.828%
7	14	295	2.419%
9	18	292	3.247%
11	22	290	3.910%

<sup>1</sup>Result of max. stress in Metal Loss-3

<sup>2</sup>Voltage reduction compared to the condition without repair

Furthermore, sensitivity analysis is carried out by providing plastic collapse load conditions for each variation in the number of ply, the results are contained in Table 26.

**Table 12. Results of sensitivity analysis on plastic collapse loads**

Number of <i>ply</i> near ML	LF
<i>W.O Repair</i>	2.109
5	2.326
7	2.327
9	2.328
11	2.329

In addition to the number of composite thicknesses, analysis was also carried out by varying the patch overlap configuration against metal loss. The part that is used as a variation of the patch configuration is in the metal loss section 3.

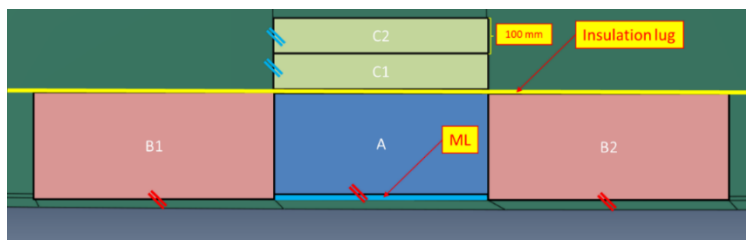


Figure 17. Composite patch configuration variation code

The results of the analysis of the variation of the composite patch configuration are shown in Table 13, the load conditions given in this analysis are the design operating conditions.

Table 13. Analysis results of composite patch configuration variations

NO.	Number of ply near ML	Configuration					Max. Stress <sup>1</sup> (MPa)
		A	B1	B2	C1	C2	
1							299.3
2							296.8
3	5						299.3
4							299.2
5							296.7

### Composite Patch (COMPACT) Test Specimen Testing

Due to the absence of test standards relating to steel plates with defects patched with composite patches, the dimensions of the test specimens are determined based on the capabilities of the available tensile testing machine, along with the existing patching scheme. The purpose of this test is to determine the effect of the addition of composite patches on the maximum load that can be withstood by steel plates with defects. In general, the test specimen is shown in Figure 18.

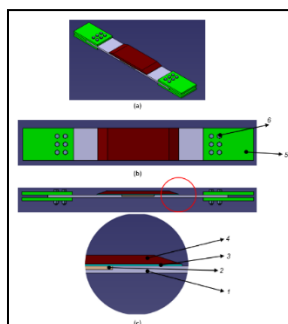


Figure 19. Overview of the test specimen, (a) Isometric, (b) Top view, and (c) Front view, along with details of the patch area.

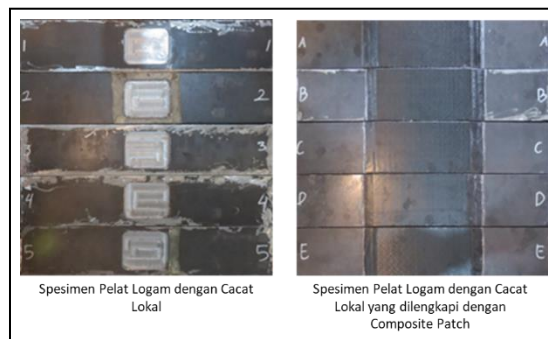
In general, the test specimens shown in Figure 19 above have the arrangement of test specimens shown in Table 14.

**Table 14. test specimen**

No.	Part Name	Specimen/Component Provider
1	Steel Plate with defects	KPI
2	Filler Material	Composite Vendor
3	Adhesive	Composite Vendor
4	Composite laminate	Composite Vendor
5	Fixture Plates	PT LAPI ITB
6	Fixture Bolts	PT LAPI ITB

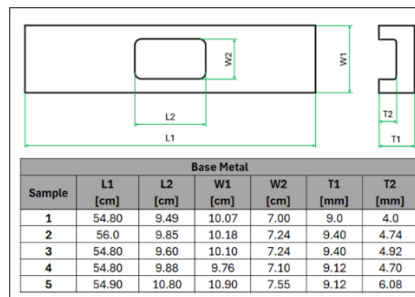
**Visual Inspection and Sample Measurement**

Visual inspection is carried out to determine the as it is condition of the specimen when received and before testing. Furthermore, from all specimens received, the code is given according to the type of specimen. Samples of metal plate specimens with local defects are coded 1 - 5. And for metal plate specimens with local defects combined with composite patches are coded A - E. Documentation of visual inspection on all samples can be seen in Figure 29. And documentation for each sample is presented in APPENDIX A.

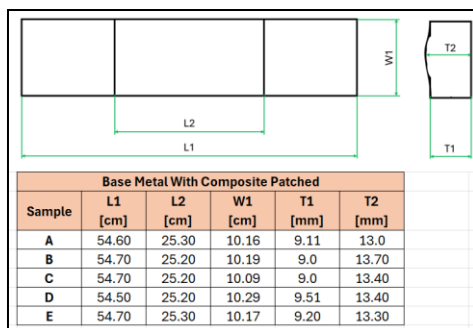


**Figure 20. Tensile Test Specimen**

In addition to visual inspection, measurements were also taken of each sample to determine the actual dimensions of each specimen. The following measurement results for each specimen are presented in Figure 15 and Figure 16.



**Figure 21. Actual Dimensions of Metal Plate Specimens with Localized Defects**



**Figure 22. Actual Dimensions of Locally Deformed Metal Plate Specimens equipped with Composite Patch**

### Test Equipment Specifications

The selection of test equipment is determined based on the actual dimensions of the entire specimen, so that the capacity of the tool used is qualified during the test (de Bekker-Grob et al., 2015). The existing tensile test equipment at the Faculty of Civil and Environmental Engineering ITB has sufficient capacity to be able to test specimens. The following description of the tensile test equipment specifications is shown in table 15.

**Table 15. Specifications of Tensile Test Equipment**

Tool Specifications	
Model	: E64.206
Rated Force Capacity	: 2000 kN
Column Configuration	: 6
Test Zones (single/dual)	: Dual
Piston Stroke	: 250 mm/min
Piston Speed	: 0.5 - 70 mm/min
Crosshead Speed	: 390 mm/min
Test Width	: 640 mm
Maximum Tensile Space	: 920 mm
Maximum Compression Space	: 950 mm
Diameter of Round Specimen	: 15 - 70 mm
Thickness of Flat Specimen	: 10 - 70 mm
Compression Platen	: 240 x 240 mm (square)
Frame Dimension (height x width x depth)	: 3150 x 1310 x 1060 mm
Weight	: 8000 kg

### Tensile Test Results

The results of tensile testing on metal plate specimens with localized defects have an Ultimate Load of 267373 N. Details of the test results can be seen in Table16, and graphs for each test specimen are presented in APPENDIX A.

**Table 16. Tensile Testing Results of Metal Plate Specimens with Localized Defects**

Specimen	Area	Yield Point	Yield Strength	Ultimate Load	Ultimate Strength
	[mm ] <sup>2</sup>	[Newton]	[N/mm ] <sup>2</sup>	[Newton]	[N/mm ] <sup>2</sup>
1	626.3	195397	311.99	295734	472.19
2	613.74	176091	286.91	268508	437.49
3	593.19	183217	308.87	271843	458.27
4	556.41	174689	313.96	271615	488.16
5	535.04	158042	295.38	229165	428.31
Average	584.936	177487.2	303.422	267373	456.884

The tensile test results on metal plate specimens with local defects equipped with composite patches have Ultimate Load 1 at an average of 295803 N, while for Ultimate Load 2 at an average of 286561 N. Details of the test results can be seen in table 17.

**Table 17. Testing Results of Locally Deformed Metal Plate Specimens which is equipped with Composite Patch**

Specime n	Area	Ultimate Load 1	Ultimate Load 2	Ultimate Strength	Equivalent Ultimate Strength*
	[mm ] <sup>2</sup>	[Newton]	[Newton]	[N/mm ] <sup>2</sup>	[N/mm ] <sup>2</sup>
A	-	287940	290258	-	-
B	-	296838	279554	-	-
C	-	317134	316746	-	-
D	-	290072	271531	-	-
E	-	287031	274716	-	-
Average	584.93 6	295803	286561		505

\*Equivalent Ultimate Strength is calculated based on the average area of metal plates with defects

With the addition of composite fillings, there was an increase;

- Ultimate load of 9.6%,
- Equivalent Ultimate Strength by 10%.

Based on the calculation of FFS Level 1 and Level 2, the tank with metal loss defects does not meet the acceptance criteria of FFS Level 1 and Level 2. So the assessment process needs to be continued to FFS Level 3. FFS Level 3 assessment is carried out with two applicable failure modes, namely global criteria/Protection Against Plastic Collapse (PAPC), and local criteria/Protection Against Local Failure (PALF). In line with previous research conducted by (Yang et al., 2022) stated that the economic impact of crude oil supply disruptions on social welfare losses can be significant, as such disruptions lead to increased fuel prices, decreased industrial productivity, and increased transportation costs, all of which negatively affect consumers and businesses. Increasing the availability of crude oil tank inventory stocks, through increased

storage capacity and more efficient inventory management, helps mitigate these disruptions by ensuring a stable and reliable fuel supply. Strategic petroleum reserves (SPRs) play a critical role in maintaining national energy security during supply crises, enabling fuel price stabilization and reduced welfare losses. By optimizing tank inventory management and expanding reserves, countries can better manage supply shocks, protect social welfare, and reduce the negative economic impact of crude oil shortages, ultimately improving fuel security and maintaining economic stability (Yuan et al., 2020).

The study results based on the global criteria, Protection Against Plastic Collapse (PAPC), indicate that the 42-T-101B storage tank with defects does not meet the FFS Level 3 acceptance criteria under the design operating conditions (MAFH=13,990 mm) when using a Resistance Strength Factor (RSFa) of 0.9. This means that, under these conditions, the tank's structural integrity is at risk of failure due to plastic collapse, which occurs when the stresses exceed the material's ability to maintain its shape without undergoing permanent deformation. As a result, the tank is considered unsafe for continued operation without further mitigation to address the defects and reduce the potential for collapse.

On the other hand, when the assessment is carried out based on the local criteria, Protection Against Local Failure (PALF), the 42-T-101B storage tank with defects does meet the FFS Level 3 acceptance criteria under the same design operating conditions (MAFH=13,990 mm) and with an RSFa of 0.9. This suggests that, while the tank may be prone to failure under broader, more global stress conditions (such as plastic collapse), the local failure potential is within acceptable limits, meaning that the tank could still perform safely under certain localized conditions. However, this finding also highlights that the tank's overall safety may be compromised in other failure modes, and additional remedial measures may be necessary to ensure full compliance with FFS Level 3 criteria.

Based on the results of points 2.a, and 2.b above, it can be concluded in general that the 42-T-101B storage tank with defects does not meet the FFS Level 3 acceptance criteria (with RSFa 0.9 and MAFH = 13990 mm). By not mitigating the existing defects in the 42-T-101B storage tank, the results of additional analysis show that the 42-T-101B storage tank with defects can meet the FFS Level 3 acceptance criteria, with the following options;

- a. By continuing to use RSFa=0.9, the MAFH must be reduced to a maximum of 13200 mm.
- b. Using the modified RSFa, which is 0.84. By using RSFa=0.84, the MAFH can be maintained in accordance with the design condition of 13990 mm.

A defect mitigation analysis on the 42-T-101B storage tank in the form of non-metallic/composite repair has been conducted, with the following results;

- a. Under operating load conditions, where the stress level in the tank is still below the plastic stress, the addition of composite patches to the defect area will reduce the stress level in the defect area. However, this stress drop is relatively small.

- b. In loading conditions until plastic collapse, where the stress level in the tank has passed the plastic stress, the effect of composite patches will be more significant in increasing the Plastic Collapse Load of the tank.
- c. The composite patch overlap in the circumferential direction is less significant in reducing stress than the composite patch overlap in the axial (elevation) direction.
- d. With the composite patch overlap (minimum 5 layers), the Plastic Collapse Load Factor increased to 2.326, from the previous (without repair) 2.109.
- e. By mitigating the overlap composite patch, the 42-T-101B storage tank can meet the FFS Level 3 acceptance criteria with a design MAFH of 13990 mm, and  $RSFa=0.9$ .

The results of the residual age study are as follows:

- a) if no repair is carried out, and MFH is at the level of 13200 mm, and by using RSF 0.9, then tank 42-T-101B has a remaining life of 10 years (thickness limit 26.47 mm).
- b) if no repair is carried out and MFH is at the level of 13990 mm, and by using RSF 0.84, then tank 42-T-101B has a remaining life of 16 years (thickness limit 26.44 mm).
- c) if a non-metallic repair is performed and the MFH is at the 13990 mm level, and using an RSF of 0.9, then tank 42-T-101B has a remaining life of 62 years (thickness limit of 26.21 mm). This is assuming no degradation of the composite material used.

Thus, storage tank 42-T-101B with metal loss defects failed to meet the acceptance criteria under FFS Levels 1 and 2, requiring further assessment under FFS Level 3. Evaluation under the global criterion (Protection Against Plastic Collapse) indicates that the structural integrity of the tank is at risk of failure due to plastic collapse unless mitigation measures are taken. However, the tank meets the criteria under local failure conditions (Protection Against Local Failure). By adjusting the Resistance Strength Factor ( $RSFa$ ) or reducing the Maximum Allowable Fill Height (MAFH), the tank can meet the FFS Level 3 criteria. In addition, composite patch repair can improve the tank's ability to withstand pressure, thereby extending its service life to 62 years, assuming no material degradation.

## CONCLUSION

This research successfully addresses the critical issue of assessing and ensuring the structural integrity of storage tank 42-T-101B through the application of Fitness-for-Service (FFS) procedures outlined in API 653 and API 579. The study found that the tank initially failed to meet FFS Level 1 and 2 criteria due to metal loss defects, and further FFS Level 3 analysis revealed that while the tank met local failure criteria (PALF), it did not satisfy global failure criteria (PAPC) under design operating conditions. Proposed mitigation measures, including reducing the maximum allowable fill height (MAFH) to 13,200 mm or adjusting the  $RSFa$  value, along with composite patch repair strategies, demonstrated the potential to restore the tank's structural integrity and extend its remaining life to 62 years. These findings not only ensure the continued safe operation of PT Kilang Pertamina's storage tanks but also provide a valuable framework for managing

similar infrastructure challenges in the future. The study's contributions extend to offering practical insights into defect mitigation, lifespan extension, and adherence to industry standards, setting a benchmark for optimizing storage infrastructure in the oil and gas industry and reinforcing Indonesia's energy security.

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