Analysis of Surface Defects on RAM BOP with Non-Destructive Testing and Crack Propagation Simulation to Detect Potential Crack Development

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Abstract

Blowout Preventers (BOPs) are critical safety devices in drilling operations and operate in abrasive, high-pressure environments that accelerate wear and failure. This study applies two Non-Destructive Testing (NDT) methods, Liquid Penetrant Testing (LPT) and Magnetic Particle Testing (MPT), to identify surface defects on RAM BOP components, and integrates finite-element-based crack propagation simulation to assess the risk of further damage. LPT was applied to coated/non-ferromagnetic parts, while MPT was used for ferromagnetic components, referencing ASME Section V acceptance criteria. Inspections revealed defects including a 4.9 mm crack on the piston shaft and pitting corrosion (≈0.8-5.3 mm) on several parts (e.g., cavity upper, housing). The simulation, with 3000 psi operating pressure and an initial flaw (l = 3 mm; h = 1 mm; r = 0.6 mm), predicted stress concentration at the crack tip (up to ~141 MPa) and potential growth toward ~7.9-11.7 mm if unrepaired. Recommended actions include re-welding cracked regions and polishing minor scratches/pitting, combined with periodic NDT for early detection. The integrated NDT-simulation workflow supports proactive maintenance, enhances operational safety, and mitigates failure risk.

INTRODUCTION

Blowout preventers (BOPs) serve as the ultimate engineering safeguard against kicks and blowouts during drilling, with failures potentially resulting in catastrophic human, environmental, and economic repercussions. As drilling operations advance into

deeper waters and more severe conditions, concerns regarding the reliability of BOP subsystems (such as rams, control systems, annulars, and hydraulic regulators) have intensified. These concerns underscore the necessity for stringent inspection and risk-based maintenance systems that ensure the integrity of these safety devices under demanding operational conditions [1]. Examinations of global failure data reveal that leakage from elastomer degradation and function-test findings are prevalent, underscoring the necessity of systematic maintenance and verification protocols [2].

While traditional inspection methods such as visual checks and periodic function testing provide some degree of reliability assessment, they fail to fully address the dynamic nature of component degradation, especially under cyclic loading conditions [3]. This gap in predictive capability where surface defects may evolve into critical structural failures over time necessitates the development of more comprehensive approaches. Specifically, the integration of Non-Destructive Testing (NDT) methods, such as Liquid Penetrant Testing (LPT) and Magnetic Particle Testing (MPT), with Finite Element Analysis (FEA) to model crack propagation is crucial in understanding how existing flaws evolve under operational stresses [4, 5] .

LPT & MPT are widely employed surface-sensitive NDT methods for well-control equipment. LPT employs capillary action to reveal surface discontinuities on non-ferromagnetic or coated components after thorough washing and the application of a developer. The chance of detection is affected by elements such indication size, surface condition, and process parameters (e.g., dwell periods, excess removal strategies) [6]. MPT, conversely, magnetizes ferromagnetic substances and employs the attraction of magnetic particles to leaky fields over fissures. Recent advancements in MPT include improving field adequacy and signal analysis, integrating objective magnetic-field evaluation and automation to enhance detection dependability [7]. In BOP assemblies containing ferromagnetic components (e.g., housings, shafts, ram blocks) alongside non-ferromagnetic or coated components, the integration of LPT and MPT ensures comprehensive coverage for subcomponents with complex geometries and stress concentrators (e.g., ring grooves, fillets, threads).

NDT is essential for detecting surface and near-surface defects, supplying crucial information for evaluating material integrity prior to potential catastrophic failures [8]. Nonetheless, the difficulty persists in linking the surface imperfections identified by NDT with the possible progression of cracks and the deterioration of structural integrity over time [9]. Existing methodologies inadequately account for the evolution of these flaws under cyclic pressure and the repetitive loading and unloading conditions that BOPs commonly experience during operation. Reliability evaluations of BOP control systems reveal the influence of redundancy strategies and component failure/repair rates on availability, necessitating preventive methods that integrate functional testing with condition data. Excessive testing can paradoxically diminish availability owing to downtime and degradation, underscoring the necessity of optimizing the scope and frequency of inspections by leveraging data from NDT indications, functional assessments, and service records.

Fatigue crack propagation under cyclic loading is generally characterized by Paris-type rules, which correlate the fracture growth rate with the stress-intensity range and a geometric factor. Thus, finite-element analysis (FEA) integrated with NDT measurements of defect dimensions enables the evaluation of localized stress and crack-propagation pressures, assisting in decisions on repair versus return to service. This study seeks to integrate NDT with FEA simulations to predict crack propagation over time, facilitating a dynamic examination of defect evolution under cyclic loading circumstances [10, 11]. This work employs NDT techniques, specifically LPT for non-ferromagnetic or coated components and MPT for ferromagnetic parts, to elucidate the initial defect sizes and positions in BOP components. These measurements will be integrated with FEA-based

crack propagation simulations, providing actionable insights into prospective fracture formation and the component's capacity to endure repeated pressure cycles amid flaws.

Industrial and national experiences highlight the importance of regular NDT in oil and gas equipment, with Indonesian case studies illustrating the effectiveness of LPT and MPT for field inspections of drilling structures and pressure components. These inspections adhere to defined standards and offer decision criteria for repair (e.g., rewelding), blend-grind/polish, or re-inspection [12]. When integrated into a preventative maintenance program, these processes can convert first surface signs into targeted interventions prior to the emergence of through-wall cracks or sealing failures. The amalgamation of NDT and FEA simulation represents a substantial enhancement in proactive maintenance methodologies, delivering accurate forecasts regarding the timing and location of required repairs prior to catastrophic failure.

This research aims to employ LPT and MPT for the non-ferromagnetic/coated and ferromagnetic elements of the RAM BOP undergoing recertification. The study evaluates signals relative to approval criteria and conducts FEA-based fracture growth analysis under simulated internal pressure. The objective is to transform surface signs into quantitative risk evaluations and targeted maintenance actions that enhance operational safety and availability.

EXPERIMENT AND NUMERICAL METHODS

The inspected unit is a RAM BOP undergoing Recertification of Performance as part of preventive maintenance. NDT acceptance/rejection followed ASME Section V Article 6 (for LPT) and relevant MPT clauses, including linear (L)/rounded (R) indication limits.

Liquid Penetrant Testing (LPT)

The Liquid Penetrant Testing (LPT) method consists of three main elements that support each other in the material inspection procedure: cleaner, penetrant, and developer. The initial step in LPT is cleaning the surface of the material to be tested. In this stage, a cleaner is applied to remove contaminants such as oil, dust, dirt, or other residues that could hinder the penetration of the penetrant liquid. Cleaning effectiveness

(a)

(b)

(c)
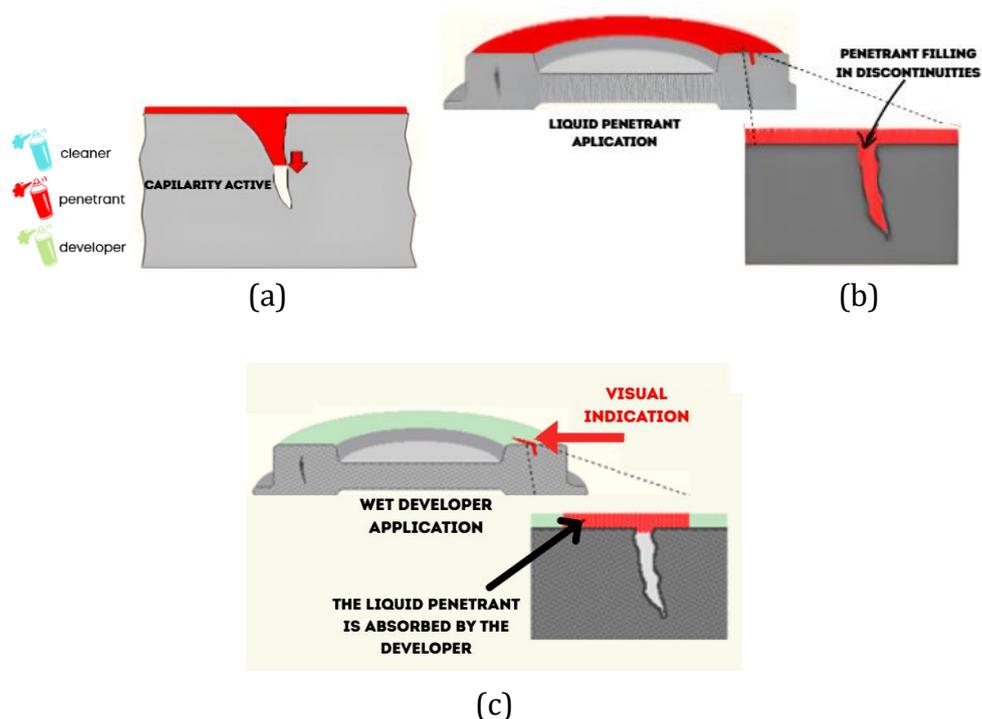
Figure 1. (a) Penetrant capillary process, (b) Liquid penetrant on defects, (c) Defect detection on the surface

is crucial because if the surface is not clean, the penetrant liquid cannot enter existing pores or cracks, which impacts the accuracy of the inspection results.

After the material surface is cleaned, a red-colored penetrant liquid is applied evenly to the material surface. The penetrant application is done thru spraying to ensure even distribution of the liquid across the entire area being tested. After the penetrant application, the next step is the dwell time. In the case of BOP, the dwell time process lasts for ten minutes [13] . During this period, the penetrant is given the opportunity to seep into cracks, pores, or hidden defects present in the material. This process allows the penetrant liquid to fill micro-gaps in the material and identify hidden defects.

After the rest period ends, the next step is the application of the developer. The developer functions to draw out the penetrant trapped in cracks or pores to the surface of the material, thus producing clearly visible defect indications. This indication will facilitate the observation and assessment of the quality of the tested material. The overall process of this LPT allows for the detection of surface defects with high accuracy and provides valuable information for further assessment of material integrity. Figure 1 represents the LPT process on the surface of defects.

Magnetic Particle Test (MPT)

The Magnetic Particle Testing (MPT) method is performed using an AC yoke (50/60 Hz; pole distance approximately 75-150 mm) and visually visible wet particles. The initial process in MPT is to clean the surface of the material to be tested. The surface is tested by removing oil and dirt (degreasing) and light abrasion if necessary to prepare a clean and contamination-free surface. After cleaning, the surface is coated with a fast-drying white contrast paint (≈15-40 μm) to enhance the visibility of indications that appear during inspection.

The illumination of the tested components was also examined to ensure that the ambient lighting in the testing location meets the minimum standard of ≥1000 lux. Prior to the commencement of production scanning, the performance of the yoke and the direction of the magnetic field are verified by conducting a lift force examination in accordance with standards (minimum ~10 lb/4.5 kg) to ensure the accuracy of the magnetic field generated by the yoke.

During the inspection, Magnaflux magnetic particles are continuously applied while the yoke is energized. The yoke will be positioned on components with uncertain defect orientation, and magnetization will be performed in two orthogonal directions, ensuring complete contact over the entire yoke leg. This enables the detection of defects in various material orientations [14] .

Indications of defects detected during inspection are recorded in real-time and documented with pictures and dimensions to facilitate further analysis and evaluation. Defect indications are evaluated and classified based on acceptance criteria: linear cracks
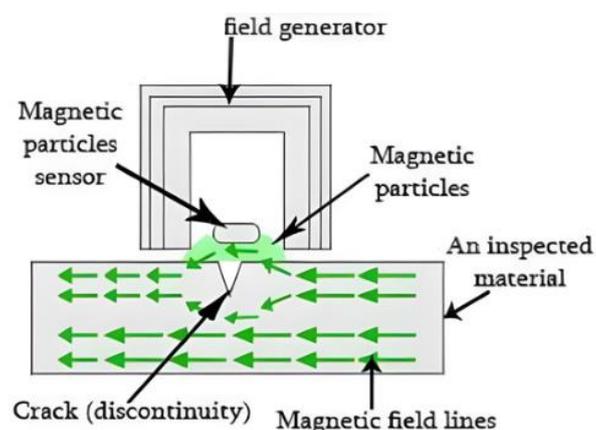

Figure 2. Working principle of MPT

will be scheduled for repair or rewelding, while shallow holes or scratches will be analyzed for smoothing or polishing processes, and non-critical indications will be monitored and rechecked at specified times. The operational principle of this MPT can be seen in Figure 2.

Crack Propagation Simulation

Simulations of fracture propagation were performed to evaluate the likelihood of crack formation in components containing undiscovered defects. This study explicitly applied the simulation to the operational piston, a vital component that had previously undergone NDT inspection and serves as a dynamic moving element in the RAM BOP system. The running piston is particularly vulnerable to heightened stress when unexpected pressure arises from the borehole, so minor cracks that may have gone unnoticed during the initial examination can progress more swiftly. The simulation utilized Ansys finite element analysis (FEA) software and had three primary phases: pre-processing, processing, and post-processing. This simulation seeks to ascertain the degree to which cracks may form on the operating piston in the absence of prompt preventive actions. The crack propagation mechanisms and material properties of the BOP components are shown in Figure 3 and Table 1.

a. Pre-processing: The pre-processing phase involves

The pre-processing stage begins with the creation of geometry from the SolidWorks design, which is then meshed using tetrahedral elements. The crack area received special attention with a fine mesh resolution of 0.2 mm to accurately capture the cracking behavior. The resulting mesh quality is considered very good (skewness 0.3), allowing it
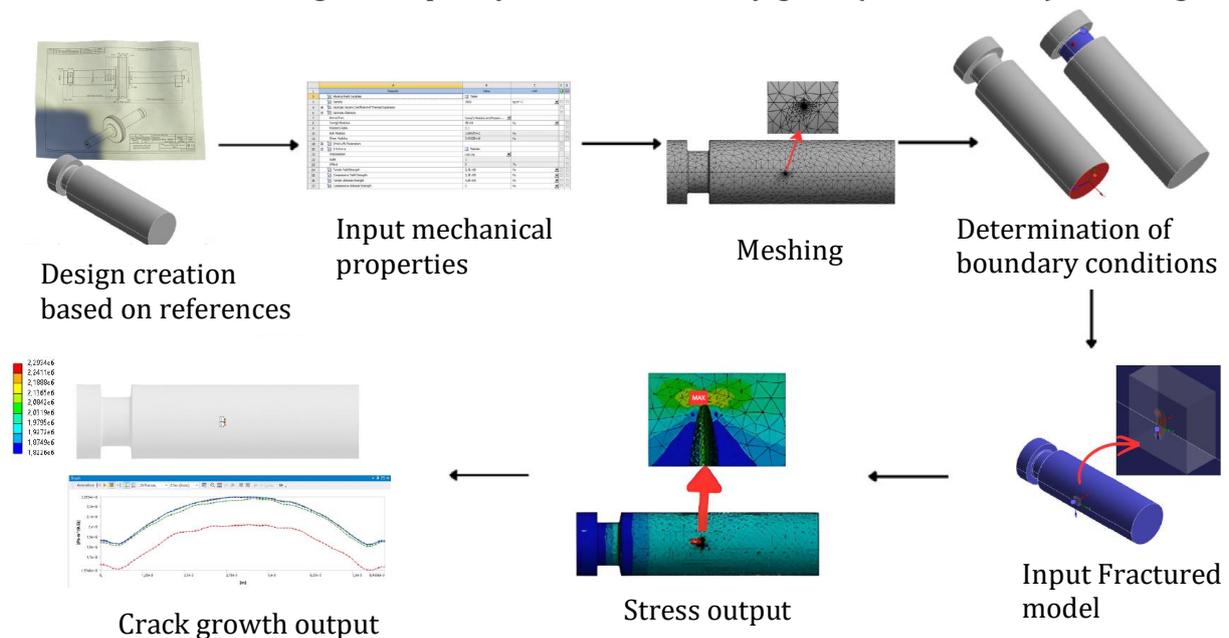
Figure 3. Crack propagation mechanism

Table 1. Material properties of BOP components

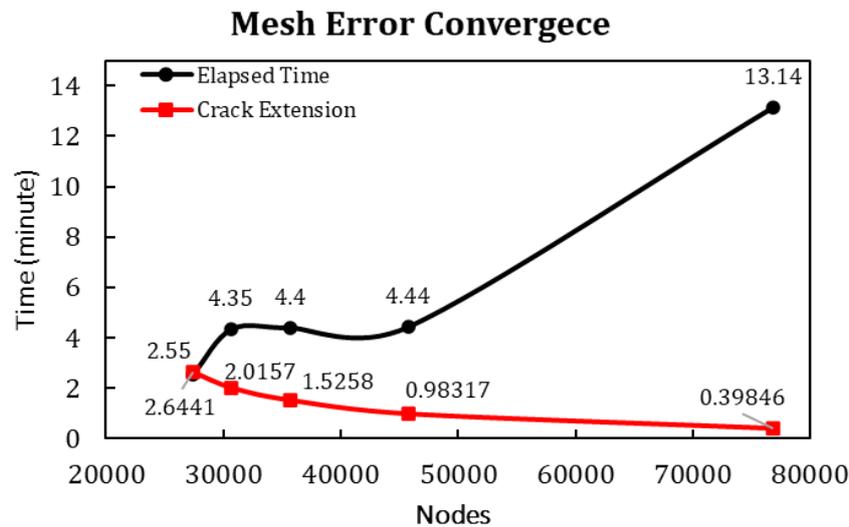| Type of properties	Value
Density	7850 kg/m^3
Young's Modulus	2E+11 Pa
Poisson's Ratio	0.3
Compressive Yield Strength	2.5E+08 Pa
Tensile Yield Strength	2.5E+08 Pa
UTS	4.6E+08

Figure 4. Mesh error convergence study graph

Table 2. Results of mesh convergence study on crack extension results

Exp.	Nodes	Elapsed Time (minute)	Crack Extension (1s)	Error (%)
1	27391	2.35	2.6441	5.635
2	30708	4.35	2.0157	4.058
3	35695	4.40	1.5258	2.829
4	45774	4.44	0.98317	1.467
5	76843	13.14	0.39846	-

to accurately represent the crack tip and the surrounding stress field. The mesh convergence study revealed that, although Experiment 5 produced small errors, its simulation time per second was relatively longer. Based on the optimal balance between accuracy and computational efficiency, Experiment 4 was subsequently selected as the optimal configuration because it offered shorter solution times with an insignificant increase in error. The considerations for selecting the optimal mesh, taking into account execution time and error rate, are detailed in Table 2 and Figure 4.

Boundary conditions for the simulation are then established, with a pressure of 3000 psi applied to the model, simulating the operational environment of the BOP. The initial fissures are defined based on NDT findings and quality control data. These fissures, with dimensions of l = 3 mm, h = 1 mm, and r = 0.6 mm, were modeled as starting points for crack propagation.

b. Processing: The processing phase entails

During the processing phase, the FEA solver in Ansys performs S.M.A.R.T. crack growth analysis, which combines static crack growth and fatigue crack growth (Paris law). The mathematical model is shown in equations 1-3. This law links the crack growth rate (da/dN) to the stress intensity range (ΔK), where:

$$\frac{da}{dN} = C(\Delta K_{eq})^m \tag{1}$$

$$K = Y \cdot \sigma \sqrt{\pi a} \tag{2}$$

$$\sigma = \frac{F}{A} \tag{3}$$

Here, C is a material constant, and m is an exponent depending on the material properties and loading conditions. The variation in the stress intensity factor (ΔKeq) is used to model the crack propagation, simulating how the crack will expand over time due to repeated stress cycles.

c. Post-processing: The post-processing phase includes

In the post-processing phase, the results of the simulation are visualized. Key outputs include the stress distribution across the component surface, focusing on areas with the highest stress concentration. These areas are where cracks are most likely to propagate. Stress values on the fractured component are displayed, showing both the peak stress at the crack tip and the overall stress distribution on the rest of the component. Additionally, the crack growth progression is analyzed, with future crack lengths predicted based on the simulation. This enables the identification of potential failure zones and the estimation of stress at which point failure may occur. The results of this simulation are critical for determining repair actions. Areas showing significant stress concentrations or excessive crack growth predictions are flagged for early intervention. In contrast, areas that exhibit negligible crack growth can be monitored for future inspections.

RESULTS AND DISCUSSIONS
NDT Findings

Representative LPT symptoms were pitting on the upper cavity (~5.3 mm) and slight scratches on the cylinder piston and balance stem. A crack measuring approximately 4.9 mm was detected on the piston shaft. MPT identified corrosion and pitting (about 0.8-1.2 mm) on the housing and ram block-pipe ram, along with a ~4.9 mm crack in the RX-45 ring groove. Acceptance determinations adhered to ASME standards; re-welding was advised for cracks, polishing for minor scratches and pits, with subsequent monitoring required.

The NDT test results suggest that the identified defects, including pitting and tiny scratches, may deteriorate the structural integrity of the components if not promptly remedied. Surface non-destructive testing methods, specifically liquid penetrant testing (LPT) and magnetic particle testing (MPT), consistently uncover fine linear indications and sub-millimeter pitting that are frequently overlooked during standard visual inspections, demonstrating enhanced detection reliability when field conditions and contrast are adequately managed [15]. Pitting identified on components can diminish material thickness, generate weak areas that compromise the component's integrity, and elevate the likelihood of structural failure [16, 17]. With time, unaddressed pitting will deteriorate the material's integrity, particularly when components are subjected to elevated pressure and severe operating conditions [18]. Minor scratches on certain components may expedite material degradation and serve as ingress locations for corrosion, thereby deteriorating the condition and jeopardizing component function over time [19]. Moreover, untreated cracks in moving components would considerably deteriorate the state of the component cracks may enlarge with heightened usage cycles, intensifying stress concentration at the fracture tip and hastening the crack's propagation [20]. In the absence of rectification, these fissures may result in catastrophic structural failure, entirely compromising components and jeopardizing operating safety [21]. Consequently, rewelding in regions with discovered cracks and polishing minor scratches are essential repair actions to avert additional damage, preserve component integrity, and enhance long-term operational safety [22].

Potential for Crack Development

The modeling results regarding crack propagation in the RAM BOP component, illustrated in Figure 5(a), underscore the need for early detection and intervention to

prevent more severe structural damage. The initial crack position identified by LPT/MPT aligns with inspection findings (Table 3-4) and was used as the initial flaw condition in the Paris' law-based simulation model, showing that the crack initiating from the surface indication (initial dimensions l = 3 mm; h = 1 mm; r = 0.6 mm) continues to propagate. The initial image shows the stress distribution on the component surface, with the red area indicating a peak stress concentration of 141.3 MPa at the crack tip. Stress can increase as cracks spread throughout the region. High working pressure of 3000 Psi can damage material integrity and accelerate failure if repairs are not made. Increased voltage application in that area correlates with an increased probability of crack formation, especially when the component is subjected to continuous repeated loading. Figure 5(b) illustrates the homogeneous stress contours on the component surface under ideal conditions, with a maximum stress of 127.68 MPa. Based on these two stress results, it can be concluded that defects in a RAM BOP component can increase stress by up to 10.12%.

Table 3. Indications of LPT surface defects

No	Name	Interpretation		Recommendations for improvement	Inspection Result	
		Condition	Size(mm)		ACC	Reject
1	Cavity Upper	Pitting	5.3;L	Re-Weld		✓
2	Cylinder Piston	Minor Scratch	Ø.2;R	Polishing	✓	
3	Balance Stem	Minor Scratch	Ø0.3;R	Polishing	✓	
4	Ram Change Piston	Minor Scracth	2.8;L	Polishing	✓	
5	Piston Shaft	Crack	4.9;L	Re-Weld		✓

Table 4. Indications of MPT surface defects

No	Name	Interpretation		Recommendations for improvement	Inspection Result	
		Condition	Size(mm)		ACC	Reject
1	Housing, locking screw	*Corrosion*	Ø 0.8;R	*Polishing*	✓	
2	Ram block-pipe ram	*Corrosion*	Ø 1.2;R	*Polishing*	✓	
3	Intermidite	*Corrosion*	Ø 1.1;R	*Polishing*	✓	
4	*Ring Groove* RX-45	*Crack*	4.9;L	*Re-Weld*		✓

Figure 5 (c) illustrates the correlation between fracture propagation and the applied load on the component. The graph illustrates that, in the absence of remedial measures, the crack will persist in propagating, resulting in an escalation of the stress intensity factor (K) near the fracture tip. The maximum K value occurs at fracture conditions of 4 mm and 7.9 mm, with the possibility of progression up to 11.67 mm. This escalation results in localized failures in the exposed regions, potentially diminishing structural integrity dramatically. This indicates that, over time, fissures can form swiftly and considerably diminish the structural integrity of components [23]. The component is susceptible to catastrophic failure if utilized in this condition. This simulation demonstrates the significance of performing regular inspections utilizing NDT techniques to identify cracks at an early stage [24, 25].

According to the NDT findings and the possibility of significant fracture progression, the suggested repair procedures entail rewelding in regions with substantial cracks and polishing in areas with mild abrasions, including piston cylinders and balance shafts. Additional prevention can be accomplished by choosing materials with enhanced resistance to cracking, including those exhibiting high fatigue and corrosion resistance, and by utilizing protective coatings to mitigate the risk of damage. Moreover, preventive maintenance via regular inspections employing NDT techniques such as LPT and MPT is essential for the early identification of surface flaws. It is highly suggested to preserve component integrity, optimize load and pressure control, and implement condition-based periodic maintenance and replacement to prevent additional damage [26, 27]. These findings underscore the functional correlation between NDT (LPT/MPT) data and FEA predictions: NDT provides realistic dimensions and location of initial flaws, while crack
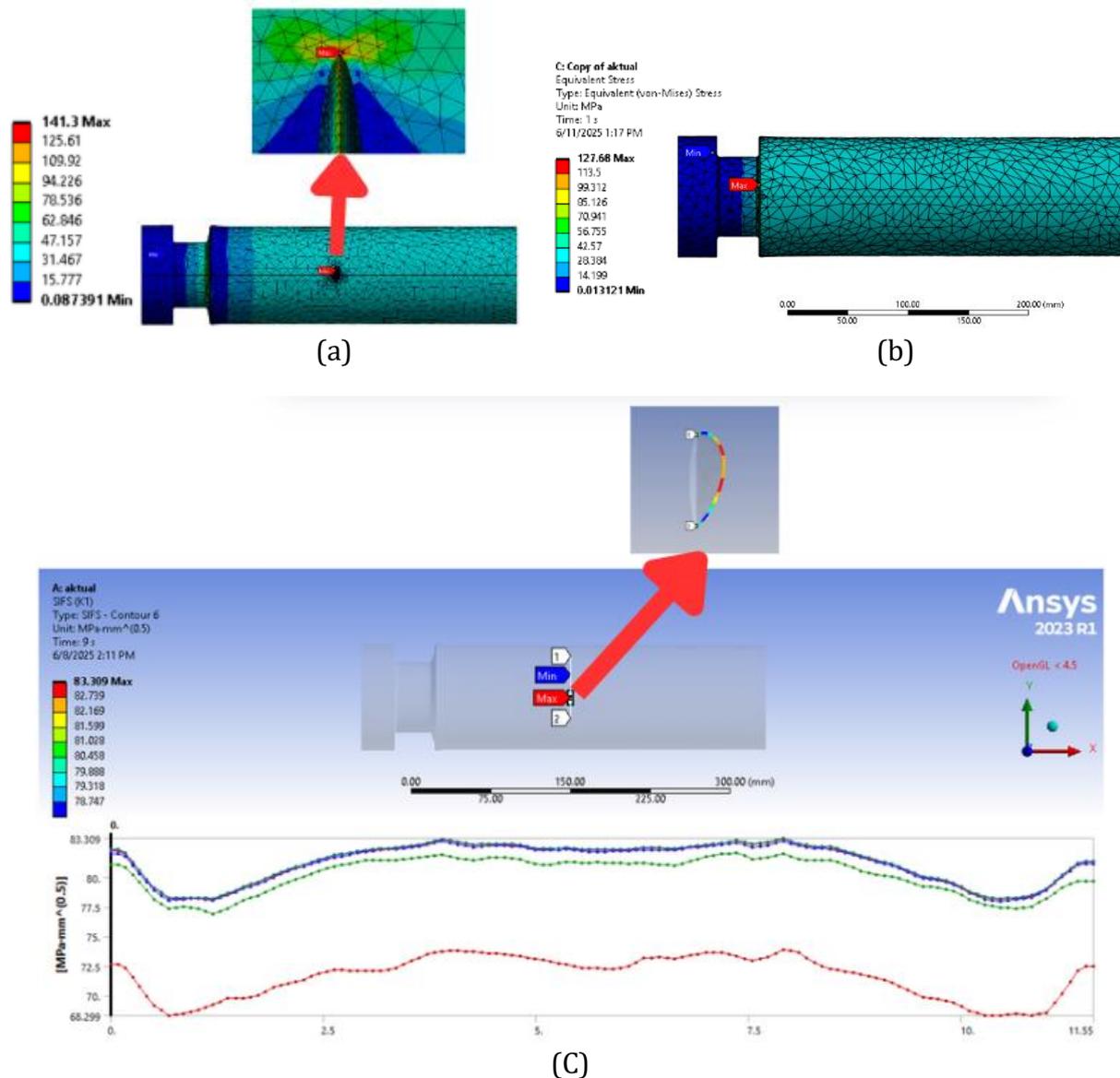
Figure 5. (a) Crack Component Stress Contour, (b) Optimal Component Stress Contour (c) SFIS Graph

propagation simulation was not only conducted to determine the increase in crack length but also to evaluate the fatigue life or the number of cycles the component can withstand before reaching a critical failure condition. Thus, the integration of NDT-FEA not only strengthens the initial inspection readings but also provides a basis for prioritizing risk-based maintenance interventions, thereby reducing the likelihood of catastrophic failure in dynamic components such as operating pistons.

CONCLUSION

This study combines NDT techniques utilizing LPT and MPT to identify surface defects in RAM BOP components. The test results reveal multiple faults, including pitting, minor scratches, and fractures, with the primary observation being a 4.9 mm crack on the piston rod. Simulation of fracture propagation utilizing Ansys software indicates that untreated cracks may extend to 11.67 mm, potentially compromising component integrity and elevating the danger of structural failure. This discovery underscores the significance of routine preventive maintenance to identify faults promptly, so averting more extensive harm. This research highlights the substantial advantages of an NDT-based methodology integrated with crack propagation simulation, offering a more proactive maintenance plan. This technique not only assesses the probability of damage

expansion but also establishes a more robust foundation for identifying the optimal timing and location for repairs. Furthermore, choosing materials with enhanced fatigue and corrosion resistance, along with the application of protective coatings, can prolong the lifespan of components.

The integration of LPT and MPT with FEA modeling improves the efficacy of monitoring and maintenance interventions, facilitating more precise forecasting of defect development. This discovery indicates that NDT can enhance condition-based maintenance for increased efficiency by prioritizing higher-risk regions according to inspection outcomes. Consequently, the proposed methodology substantially enhances operational safety and diminishes the probability of future component failures. Future study may concentrate on advancing detection technologies, including ultrasound and thermography, while also evaluating more intricate dynamic load conditions to enhance the comprehension of BOP component performance in diverse harsh operating scenarios. Additional study is required to investigate the potential of utilizing materials with enhanced mechanical properties, including those engineered to augment resistance to fatigue and corrosion damage.

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