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Finite Element Analysis and Root Cause Analysis of Wire Rope Failure in STS Cranes

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ABSTRACT

Wire rope is a critical lifting component in Ship-to-Shore (STS) cranes, whose failure can lead to catastrophic system breakdowns, posing significant safety risks and operational losses. This study investigates the root causes of wire rope failure on a 40-ton capacity STS crane. The methodology integrates Root Cause Analysis (RCA) with a Finite Element Analysis (FEA) simulation using ANSYS Static Structural. The analyzed wire rope has a 28 mm diameter, a 6x36 IWRC configuration, and is made of galvanized high-carbon steel. Simulation results under full operational load revealed a maximum von Mises stress of 681 MPa, exceeding the material's yield strength (≈650 MPa), a total displacement of 16 cm, and a critically low safety factor of 0.53. The failure location was identified on the outer strands at the contact points with sheaves, indicating high-stress concentration zones. Furthermore, the calculated Safe Working Load (SWL) for a standard safety factor of 5 was 82.83 kN, which is drastically lower than the 400 kN operational load per rope, confirming severe overstress conditions. The RCA fishbone diagram identified key contributing factors: material specification mismatch, suboptimal sheave design, inadequate maintenance protocols, and insufficient design-stage analysis. The study concludes that the wire rope is unfit for service under current conditions and recommends immediate replacement, revised preventive maintenance schedules incorporating FEA, design optimization of support components, and implementation of real-time load monitoring systems.

Keyword: *Wire Rope, STS Crane, Finite Element Analysis (FEA), Root Cause Analysis (RCA), Von Mises Stress, Safe Working Load (SWL).*

ABSTRAK

Wire rope merupakan komponen kritis pada Ship-to-Shore (STS) Crane yang berfungsi untuk mengangkat dan menurunkan peti kemas. Kegagalannya dapat menyebabkan keruntuhan sistem total, berpotensi menimbulkan bahaya keselamatan dan kerugian operasional. Penelitian ini bertujuan untuk menganalisis penyebab utama kegagalan wire rope menggunakan metode Root Cause Analysis (RCA) dan mensimulasikan distribusi tegangan serta deformasi menggunakan perangkat lunak ANSYS dengan pendekatan Static Structural. Spesifikasi wire rope yang digunakan adalah diameter 28 mm, konfigurasi 6x36 IWRC, dengan material galvanized high carbon steel. Hasil simulasi menunjukkan nilai tegangan von Mises maksimum sebesar 681 MPa (melampaui kekuatan luluh material), displacement sebesar 16 cm, dan faktor keamanan yang sangat kritis sebesar 0,53. Lokasi kegagalan teridentifikasi pada bagian terluar strand di area kontak dengan sheave, yang merupakan zona konsentrasi tegangan tertinggi. Perhitungan Safe Working Load (SWL) menunjukkan bahwa kapasitas kerja aman wire rope adalah 82,83 kN, yang jauh lebih rendah dari beban operasional crane sebesar 400 kN, sehingga memperkuat temuan bahwa wire rope telah bekerja dalam kondisi overstress yang parah. Analisis RCA mengidentifikasi akar penyebab kegagalan, yaitu ketidaksesuaian spesifikasi material, desain sheave yang tidak optimal, dan protokol pemeliharaan yang kurang memadai. Penelitian ini menyimpulkan bahwa wire rope tidak lagi layak digunakan dan merekomendasikan penggantian segera,

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optimasi desain komponen pendukung, serta penerapan jadwal pemeliharaan yang lebih proaktif.

Kata Kunci: *Wire Rope, STS Crane, Analisis Elemen Hingga (FEA), Root Cause Analysis (RCA), Tegangan Von Mises, Safe Working Load (SWL).*

1. Introduction

Indonesia, as the world's largest archipelagic nation, relies heavily on its maritime sector and port logistics for economic growth. The efficiency of port operations, particularly container loading and unloading, is paramount. Ship-to-Shore (STS) cranes are the workhorses of modern container terminals, and their operational reliability hinges on the integrity of critical components like wire ropes [1], [2].

Wire ropes in STS cranes are subjected to extreme static and dynamic loads, cyclic bending over sheaves, and exposure to corrosive maritime environments. Over time, these factors lead to performance degradation through mechanisms such as fatigue, abrasion, and corrosion [3], [4]. A failure can result in total operational shutdown, significant financial loss, and severe safety hazards.

Traditional inspection methods, while necessary, often focus on visible surface damage and may fail to predict internal stress states and impending failure. Therefore, a more robust approach combining failure analysis techniques and advanced engineering simulation is required. Root Cause Analysis (RCA) provides a systematic framework for identifying fundamental failure causes beyond immediate symptoms [5]. Meanwhile, Finite Element Analysis (FEA) offers a powerful tool to simulate and visualize complex stress distributions and deformations under operational loads, providing quantitative data that is difficult to obtain experimentally [6], [7].

This study aims to bridge this gap by employing an integrated approach. It utilizes RCA to methodically identify the underlying causes of wire rope failure on an STS crane and validates these findings through detailed FEA using ANSYS software. The objectives are to: (1) identify the root causes of failure using an RCA fishbone diagram, (2) calculate the actual Safe Working Load (SWL), and (3) simulate the stress distribution, deformation, and safety factor to pinpoint the exact failure location and assess the rope's structural integrity.

2. Methods

2.1 Root Cause Analysis (RCA)

A fishbone (Ishikawa) diagram was employed to conduct the RCA. The central problem ("Wire Rope Failure") was analyzed across five main categories: Machine, Method, Material, Maintenance, and Environment. Potential causes were brainstormed and organized under these categories to identify the most probable root causes.

2.2 Finite Element Analysis (FEA) with ANSYS

A virtual model of the wire rope system was created and analyzed using ANSYS Workbench 2024 R1's Static Structural module.

- Geometric Modeling: A macro-modeling approach was adopted due to the extreme complexity of modeling individual wires. The 28 mm diameter wire rope was modeled as a simplified 3D solid cylinder, including its interaction with sheaves and drum to replicate real-world bending and contact conditions (See Fig. 1).

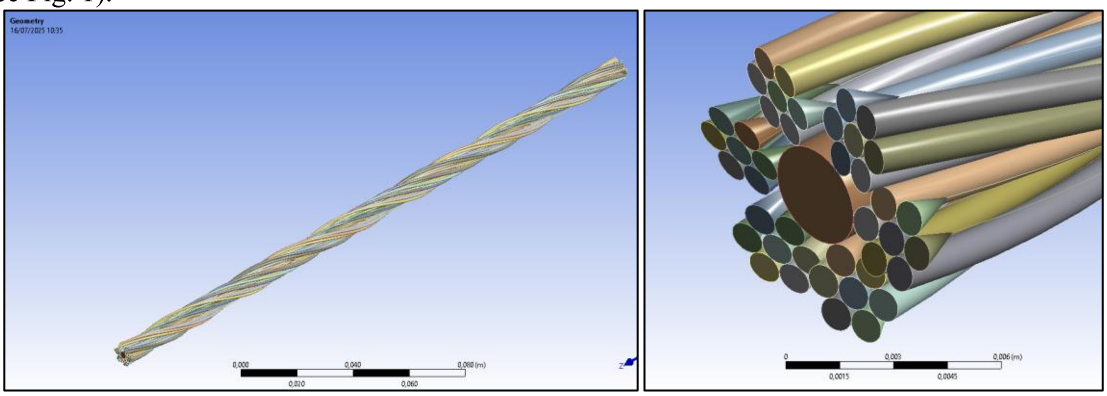

Figure 1. Macro-Model of the Wire Rope

- Material Properties: The wire rope was assigned the properties of galvanized high-carbon steel: Young's Modulus = 200 GPa, Poisson's Ratio = 0.3, Density = 8027 kg/m³, Ultimate Tensile Strength (UTS) = 1770 MPa.
- Meshing: The model was discretized using solid elements. A mesh refinement strategy was applied to areas of potential stress concentration, such as the contact regions with sheaves. The final mesh consisted of 155,243 elements and 820,360 nodes.
- Boundary Conditions and Loading: A fixed support was applied to one end of the rope (anchored to the drum). A static axial load of 400 kN (40 tons) was applied to the opposite end, representing the operational load. Frictional contact (μ=0.2) was defined between the wire rope and the sheaves.
- Analysis: The simulation solved for von Mises stress, total deformation, safety factor, and equivalent elastic strain.

2.3 Safe Working Load (SWL) Calculation

The SWL was calculated based on the Minimum Breaking Load (MBL) and an appropriate safety factor (SF). The MBL was derived from the material's UTS and the effective cross-sectional area of the rope, considering a fill factor of 0.38 for a 6x36 IWRC rope [8].

$$A=0.38\times\frac{\pi d^2}{4}=0.38\times\frac{\pi(28\times10^{-3})^2}{4}\approx 233.99\ \text{mm}^2$$

$$MBL = \text{A}\times\text{UTS} = 233.99\times10^{-6}\ \text{m}^2\times1770\times10^6\ \text{Pa}\approx 414\ \text{kN}$$

$$\text{SWL}=\frac{\text{MBL}}{\text{SF}}=\frac{414\ \text{kN}}{5}=82.83\ \text{kN}$$

3. Results and Discussion

3.1 RCA Fishbone Analysis

The RCA identified several probable root causes across the five categories (Fig. 2). The most critical were:

- Material: The specification of the 28 mm wire rope was likely insufficient for the intended 40-ton load, leading to an inherent lack of safety margin.
- Machine: Suboptimal sheave/drum design (e.g., incorrect groove radius, wear) created high-stress concentrations, accelerating fatigue and wear.
- Method & Maintenance: Reliance solely on visual inspection, without advanced techniques like FEA or real-time load monitoring, allowed the rope to operate in an overstressed condition until critical failure was imminent.
- Design Process: A lack of comprehensive analysis during the design/selection phase, including fatigue life and dynamic load assessment, led to the selection of an under-specification component.

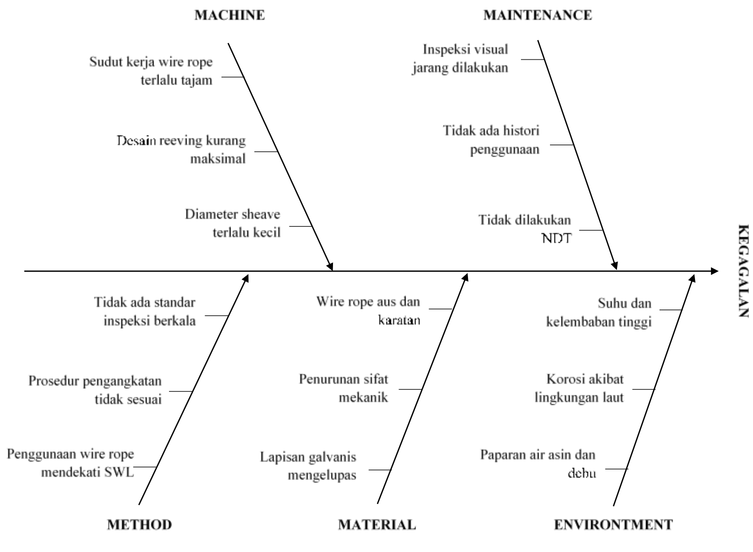

Figure 2 Fishbone (Ishikawa) Diagram for Root Cause Analysis of Wire Rope Failure

3.2 FEA Simulation Results

The ANSYS simulation provided clear quantitative and visual results on the rope's performance under load.

- Von Mises Stress: The maximum stress was 681 MPa, located on the outer strands at the contact points with the sheaves (Fig. 3a). This value exceeds the typical yield strength of high-carbon steel (≈650 MPa), indicating plastic deformation and the onset of structural failure.
- Total Deformation: The maximum displacement was 160 mm (Fig. 3b), indicating significant elastic stretching, which aligns with the high stress observed.
- Safety Factor: The minimum safety factor calculated was 0.53 (Fig. 3c). This value is critically below the industry standard of 3-5 for lifting applications [9], confirming that the wire rope is operating in a dangerous state of overstress.

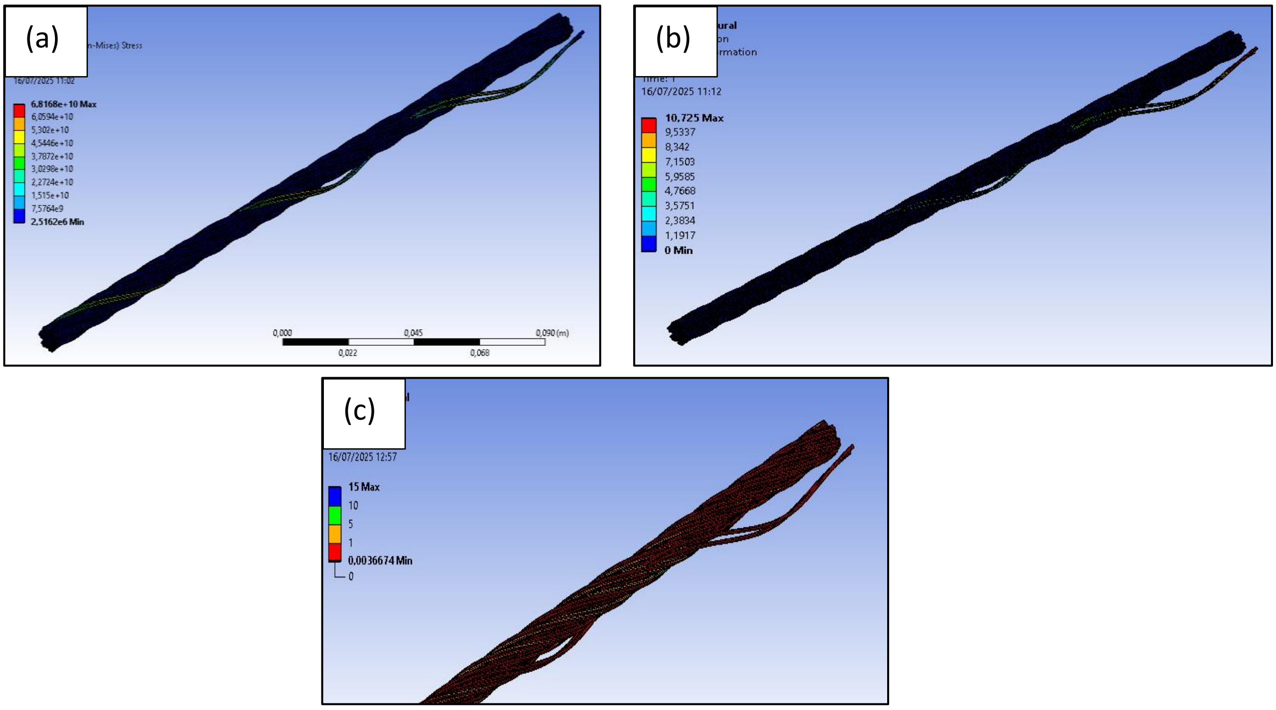

Figure 3. ANSYS Simulation Results: (a) Von Mises Stress Contour (Max: 681 MPa), (b) Total Deformation (Max: 160 mm), (c) Safety Factor Contour (Min: 0.53)

3.3 *SWL Calculation*

The calculated SWL of 82.83 kN (for SF=5) is drastically lower than the 400 kN operational load applied per rope in the simulation. This stark discrepancy confirms the primary finding from the FEA: the wire rope is grossly overloaded. Operating at 400 kN represents an effective safety factor of just above 1.0 (414 kN / 400 kN ≈ 1.035), leaving no margin for safety and directly explaining the simulated failure.

3.4 Discussion

The results from the FEA and SWL calculation are mutually reinforcing and paint a clear picture of the failure mechanism. The wire rope, as specified, is fundamentally inadequate for its assigned task. The high stress (681 MPa) causing plastic deformation, combined with a safety factor of 0.53, leaves no doubt that the rope would fail under a 40-ton load.

The identified failure location on the outer strands is consistent with established theory and ISO 4309 criteria [10]. This area experiences the highest stress due to a combination of tensile loading, bending fatigue over sheaves, and abrasive wear. The RCA findings provide the context for why this situation occurred, pointing to failures in the selection, design, and maintenance processes.

4. Conclusions

In conclusion, this integrated investigative approach, combining Root Cause Analysis with Finite Element simulation, has definitively diagnosed the critical failure of the wire rope on the STS crane. The FEA results quantitatively confirmed a state of severe overstress, evidenced by a von Mises stress of 681 MPa that surpasses the material's yield point, a significant deformation of 16 cm, and an alarmingly low safety factor of 0.53, all of which unequivocally indicate that the structural integrity of the rope was compromised under the

40-ton operational load. This numerical finding was fundamentally explained by the stark discrepancy between the calculated Safe Working Load of 82.83 kN and the actual load, revealing a profound specification error. The RCA further contextualized this technical failure, tracing its roots to systemic issues in material selection, support system design, and maintenance protocols. Therefore, it is conclusively determined that the wire rope was fundamentally unfit for its intended service, necessitating immediate replacement. This study underscores the critical importance of rigorous design validation and proactive, data-driven maintenance strategies to prevent such hazardous operational conditions and ensure both safety and reliability in port infrastructure.

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