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Failure Analysis of a Connecting Rod Bolt in a Heavy Equipment Diesel Engine

[1]*Leonardus Yudhi Prasetyo, [2]Sulardjaka, [3]Gunawan Dwi Haryadi

[1,2,3]Mechanical Engineering, Faculty of Engineering, Diponegoro University, Jl. Prof. H. Soedarto, SH, Tembalang-Semarang 50275, Indonesia
*Corresponding Author's E-mail: leoyudhi@students.undip.ac.id

Abstract - **Connecting rod bolts are critical fasteners in heavy equipment diesel engines, where their structural integrity is paramount for operational reliability. This study investigates the root cause of a connecting rod bolt fracture in a heavy equipment diesel engine which have 936 Horsepower, which precipitated a catastrophic engine breakdown involving low power, overheating, and oil leakage. The failure analysis employed visual observation, macrographic examination, and Vickers micro-hardness testing to evaluate the fracture morphology and material properties. Hardness testing results revealed a core hardness of 347 HV, confirming that the bolt material (AISI 8640) retained a proper tempered martensite structure consistent with standard specifications, thereby ruling out material deficiency or thermal degradation. Macrographic analysis identified a progressive failure sequence involving two distinct mechanisms. The primary bolt failed via High Cycle Fatigue (HCF), evidenced by a flat fracture surface and ratchet marks at the periphery, indicative of reversed bending forces. The fracture of the primary bolt caused a loss of clamping force, leading to the instantaneous failure of the remaining bolts via ductile overload, characterized by fibrous topography and shear lips. The study concludes that the root cause of the failure was mechanical joint instability (loosening), which introduced fatal bending stresses and initiated the fatigue mechanism.**

Keywords: Failure analysis, Connecting rod bolt, High Cycle Fatigue, Joint loosening, heavy equipment diesel engine.

I. INTRODUCTION

Indonesia's population, based on the 2020 census, reached 270.2 million, with a growth rate of 0.98% in 2021 according to the Central Bureau of Statistics. Population dynamics significantly influence energy demand, both directly and through their impact on economic development. Indonesia's economic growth in the coming years is projected to be supported by increasing domestic demand, including consumption and investment, as well as improved export performance, particularly in the manufacturing sector, which remains the largest energy consumer within the industrial sector. The national final energy demand under the Business as Usual (BaU), Policy-Based (PB), and Radical Change (RK) scenarios is expected to grow annually by 5.0%, 4.7%, and 4.3%, respectively, reaching 548.8 MTOE, 481.1 MTOE, and 424.2 MTOE by 2050 [1].

In terms of energy composition, Indonesia's energy mix in 2021 consisted of coal at 38%, oil at 32%, gas at 19%, and renewable energy at 11% [2]. Coal remains the dominant energy source, supported by Indonesia's substantial reserves of 34.87 billion tons, positioning the country as the seventh-largest holder of coal reserves globally [3]. With such vast reserves, coal mining continues to play a vital role in meeting Indonesia's energy needs. The mining industry itself encompasses several critical phases, including exploration, extraction, exploitation, processing, and refining [4]. Mining operations require efficient equipment management to maximize production and reduce costs. However, equipment failures, such as breakdowns of dump trucks, dozers, or other heavy machinery, can halt operations and result in significant capital losses [5]. Thus, monitoring and maintaining mining equipment is essential to ensure smooth operations.

Dump trucks are pivotal assets in open-pit mining operations, representing a substantial capital investment that accounts for 50–60% of total operational costs (Chaowasakoo dkk., 2017; Moradi Afrapoli & Askari-Nasab, 2017). Operating continuously under severe terrain conditions, these vehicles demand superior mechanical reliability [8]. While the internal combustion engine serves as the primary power source [4], its structural integrity relies heavily on the connecting rod bolts. These fasteners are critical components responsible for securing the connecting rod cap and maintaining the assembly's cohesion against high inertial forces [9]. Failure of the connecting rod bolt is particularly hazardous; it acts as the primary trigger for catastrophic engine breakdown. The fracture of a single bolt inevitably leads to the detachment of the connecting rod cap, causing severe consequential damage to the connecting rod itself, the crankshaft, and the cylinder block [10]. Such incidents result

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in significant economic losses due to unexpected downtime and high repair costs [11].

Therefore, this study conducts a comprehensive failure analysis specifically on the connecting rod bolts to determine the root cause of the fracture that precipitated the engine failure. The investigation focuses on three primary testing methods: visual observation to identify general physical damage and deformation; macrographic examination to analyze the fracture surface topography and determine the failure mode; and hardness testing to evaluate the material's mechanical properties and validate its compliance with standard specifications. Through this systematic approach, the research aims to reconstruct the failure sequence and provide recommendations to prevent fastener failure in heavy equipment diesel engine.

II. RESEARCH MATERIAL AND METHODOLOGY

Connecting rod bolt is the main material tested in this research. The bolt connecting rod tested is the connecting rod on the heavy equipment diesel engine which can be seen in Figure 1.

Figure 1: Connecting Rod Bolt Condition

2.1 Visual Observation

The failure analysis of the connecting rod bolts was initiated following the discovery of severe structural damage to the connecting rod assembly. This damage was revealed during an engine teardown, which was performed in response to operator reports of low power, overheating, and oil leakage. Consequently, the investigation focused on the bolts to determine if their failure was the primary cause of the connecting rod damage.

Upon disassembly, the investigation identified the fracture of the connecting rod bolt as the primary root cause of the assembly failure. As shown in Figure 1, the severance of the bolt led to the catastrophic detachment of the connecting rod cap. This separation resulted in a loss of structural integrity, which subsequently inflicted severe collateral damage on the connecting rod and the cap itself, as illustrated in Figure 2.

Figure 2: Connecting Rod Cap Condition

2.2 Hardness Testing

Hardness testing was performed to determine the hardness distribution across the connecting rod bolt using the Vickers method. The procedure involved creating indentations at five distinct points, traversing from the near-surface region inward. Conducted in accordance with ASTM E92 standards, this testing is critical for assessing the bolt's quality and mechanical strength. Specifically, the obtained data is compared against manufacturer specifications to verify whether the material complies with the required engineering standards.

2.3 Macrographic Testing

Macrographic examination was utilized as a fundamental investigative tool to analyze the fracture surface of the connecting rod bolt. This visual assessment focused on mapping the topography of the failed area to identify distinct morphological features, such as crack initiation sites and propagation lines. The ultimate goal of this procedure was to definitively determine the specific mode of failure (ductile or brittle) and to characterize the underlying fracture patterns, thereby distinguishing the mechanical mechanisms responsible for the component's separation.

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III. RESULTS AND DISCUSSIONS

After conducting the observation and testing process, the following results were obtained:

3.1 Visual Observation

Visual observation of the bolt components, as presented in Figure 1, revealed distinct traces of physical contact on the shank surface. Specifically, polished areas and circumferential rubbing marks were identified along the unthreaded section. Regarding structural integrity, two specimens suffered complete fracture characterized by flat fracture surfaces oriented perpendicular to the bolt axis, with no significant necking observed. In contrast, the third specimen remained intact but exhibited extreme plastic deformation, manifesting as severe bending deviation from its longitudinal axis.

Complementary inspection was performed on the connecting rod cap (Figure 3) to identify damage at the contact interface. The cap exhibited surface irregularities and massive plastic deformation, identified as a "hammering effect" caused by repetitive impact between the cap and the rod. Structural failure in such contexts is often dominated by fatigue mechanisms initiating from stress concentration zones or inherent material defects [12]. Furthermore, this condition may be exacerbated by excessive tightening torque and fretting fatigue induced by relative micro-motion between the cap and bearing [13].

3.2 Hardness Testing

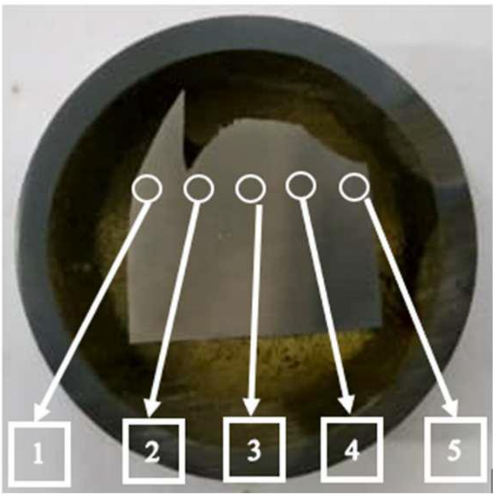


Figure 3: Vikers Micro Hardness Testing Area

To investigate the material's response to thermal and mechanical history, micro-Vickers hardness testing was performed on the transverse section of the bolt. Figure 3 illustrates the indentation trajectory. The resulting hardness values, recorded at five discrete points traversing the specimen diameter, are presented in Table 1.

Table 1: Micro Vickers Hardness Test Results

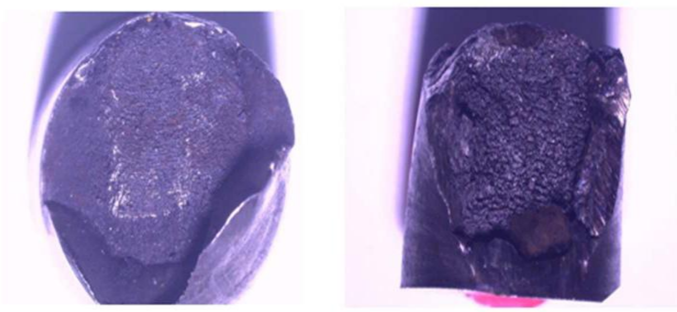
Indentation Point	Hardness Number (HRV)
1	384
2	354
3	347
4	347
5	390

As presented in the data table 1, the Vickers hardness distribution demonstrates a consistent profile ranging from a maximum of 390 HV at the periphery to a minimum of 347 HV at the core. The higher surface hardness indicates residual compressive stresses or skin deformation, which is typical for rolled threads. Analysis of this hardness profile demonstrates a stable material condition with no evidence of severe thermal degradation (overheating), which would typically result in a drastic drop in hardness. The core hardness of 347 HV (equivalent to 368 HK) serves as the most representative indicator of the bulk material's state. This value is fully consistent with the mechanical requirements for AISI 8640, a standard high-strength steel used in heavy-duty components.

The alignment of these results with the expected properties of Quenched and Tempered steel verifies the presence of a tempered martensite structure. Therefore, it can be concluded that the bolt material possesses adequate toughness and strength specifications as cited in recent studies (Triani et al., 2019), suggesting that the failure was likely driven by external loading factors rather than material deficiency.

3.3 Macrographic Testing

Macrographic inspection of the connecting rod bolts was conducted to characterize the fracture patterns, identify crack initiation sites, and determine the dominant loading conditions leading to failure. The visual findings are presented in Figure 4.



(a) (b)

Figure 4: Macrography Photo Results of Connecting Rod Bolt Fractures, (a) Bolt 1, (b) Bolt 2

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The fracture surface topography reveals two distinct failure mechanisms occurring sequentially. Specimen (a) exhibits a flat fracture surface with no significant plastic deformation (necking) and a dominant smooth propagation zone. These features confirm that failure was driven by a High Cycle Fatigue (HCF) mechanism. Notably, the presence of ratchet marks at the fracture periphery indicates multiple crack initiation origins, a condition typically triggered by reversed bending loads due to joint instability. The extensive area of the propagation zone relative to the final fracture zone suggests the bolt operated under low nominal stress but high vibration cycles, gradually reducing the effective cross-sectional area. As noted in experimental studies on high-strength bolts, fatigue cracks frequently initiate at stress concentration zones such as threads, where multi-axial loading can accelerate propagation and reduce fatigue life [15].

In contrast, Specimen (b) displays a strikingly different morphology, characterized by a rough, fibrous texture and the formation of shear lips slanted at 45 degrees along the edges. These features are hallmarks of ductile overload, where failure occurs via micro void coalescence. This phenomenon validates the material's chemical composition specifically its Nickel content which imparts high toughness, allowing significant plastic deformation prior to rupture. The distinct fracture mode indicates that this second specimen did not fail due to fatigue, but rather due to a sudden load transfer following the failure of the first bolt.

Consequently, these macrographic findings reconstruct a progressive failure chronology. The sequence initiated with joint loosening, which introduced bending forces and fatigue propagation in the first bolt. The fracture of this bolt resulted in a partial loss of clamping force, forcing the remaining bolts to bear operational loads far exceeding their yield limits. This overload caused the surviving bolts, such as Specimen (b), to fail instantaneously through ductile rupture or extreme bending deformation.

IV. CONCLUSION

The comprehensive failure analysis of heavy equipment diesel engine connecting rod bolts confirms that the failure was driven by mechanical factors rather than material deficiencies. Hardness testing results validated the material as AISI 8640 steel with a core hardness of 347 HV, indicating a proper tempered martensite structure consistent with standard specifications. Macrographic examination revealed a progressive failure sequence involving two distinct mechanisms. The primary failure occurred in the first bolt due to High Cycle Fatigue (HCF), initiated by reversed bending forces and evidenced by ratchet marks at the periphery. This fatigue fracture resulted in a loss of clamping force, causing a sudden load transfer to the remaining bolts. Consequently, the secondary bolts failed instantaneously via ductile overload, characterized by fibrous topography and shear lips. Therefore, the root cause of the breakdown is attributed to joint instability (loosening), which introduced the fatal bending stresses, rather than intrinsic material defects or thermal degradation.

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