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Comparative Finite Element Analysis of Wear Repair Methods for Vertical Kaplan Turbine Shafts Based on Structural and Dynamic Responses

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Abstract

Non-uniform journal wear on the vertical Kaplan turbine shaft increases shaft–bearing clearance, resulting in higher vibration and reduced operational reliability. This study evaluates the structural and dynamic effects of shaft wear and compares two restoration methods: Belzona 1111 coating and an SS410 stainless-steel shock sleeve. Finite Element Analysis (FEA) was performed in ANSYS Workbench using static structural and modal analyses for four shaft conditions: intact, worn, Belzona-restored, and shock sleeve-repaired. The numerical model was validated against the theoretical critical speed, yielding an error of 8.32%. The worn shaft exhibited the highest radial deformation (0.033123 mm), indicating a significant reduction in structural stiffness. Belzona restoration reduced deformation by 36.23%, while the SS410 shock sleeve achieved a 97.68% reduction, restoring shaft deformation close to the intact condition (0.00076983 mm). Although natural frequencies showed only minor variations among all cases, the shock sleeve produced the smallest deviation from the intact shaft and the most symmetrical mode shapes, indicating superior dynamic performance. The results demonstrate that journal wear primarily degrades shaft stiffness rather than natural frequencies. Among the evaluated restoration methods, machining followed by installation of an SS410 shock sleeve provides the closest structural and dynamic characteristics to the original shaft, making it the most effective solution for improving the reliability and operational stability of vertical Kaplan turbine shafts.

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1. Introduction

Hydropower plants (HPPs) are among the most reliable renewable energy sources for sustainable electricity generation. In low-head, high-flow applications, vertical Kaplan turbines are widely used because of their high hydraulic efficiency and operational flexibility. The turbine shaft plays a critical role in transmitting mechanical power from the runner to the generator while maintaining rotor–bearing alignment and overall system stability[1]. Consequently, shaft degradation can significantly reduce turbine reliability and operational performance.

Journal wear is one of the most common failure mechanisms in Kaplan turbines, resulting from prolonged contact between the shaft journal and the bearing. Progressive material loss increases bearing clearance, reduces shaft stiffness, and promotes eccentric rotor motion, leading to excessive vibration and decreased operational stability[2]. At Wonogiri Hydropower Plant Unit 2, field inspections identified non-uniform journal wear over approximately 50–60% of the shaft circumference, with a maximum wear depth of 4 mm. This damage was accompanied by vibration levels of up to 5.84 mm/s, indicating deterioration of the rotor–bearing system.

Industrial repair methods commonly include polymer composite restoration using Belzona 1111 and machining followed by the installation of an SS410 stainless-steel shock sleeve[3]. While both methods are widely applied, previous studies have primarily focused on failure mechanisms, material properties, or repair procedures. Comparative evaluations of their effects on both the structural and dynamic responses of turbine shafts, including radial deformation, natural frequencies, and mode shapes, remain limited.

Reliable structural assessment requires realistic representation of operational loads and boundary conditions. The American Society of Civil Engineers [2] emphasizes that structural performance should be evaluated under representative loading conditions to ensure accurate prediction of deformation and structural behavior. Finite Element Analysis (FEA) provides a reliable numerical approach for evaluating shaft performance under different repair conditions without interrupting plant operation. By integrating static structural and modal analyses, FEA enables comprehensive assessment of deformation, stiffness, and rotor dynamic behavior [1].

Therefore, this study investigates the effects of journal wear and compares the effectiveness of Belzona 1111 and SS410 shock sleeve repairs on the structural and dynamic performance of a vertical Kaplan turbine shaft using FEA. The novelty of this study lies in the integrated evaluation of repair performance based on both structural and modal responses, providing a more comprehensive engineering basis for selecting repair methods that restore shaft stiffness, concentricity, and long-term operational reliability.

2. Methods

This study employed a quantitative approach using Finite Element Analysis (FEA) in ANSYS Workbench to evaluate the structural and dynamic behavior of a worn Kaplan turbine shaft and its repair alternatives. Static Structural Analysis was performed to determine radial deformation, while Modal Analysis was used to evaluate natural frequencies and mode shapes (as shown in **Figure 1**). Identical boundary conditions, operating parameters, mesh configurations, and solver settings were applied to all simulations to ensure that the observed differences were caused solely by variations in shaft condition and repair material.

Field data were collected from Wonogiri Hydropower Plant Unit 2, including maintenance records, vibration measurements, shaft dimensional inspections, bearing clearances, and runner blade clearances. A Root Cause Failure Analysis (RCFA) was first conducted to identify the primary causes of shaft degradation.

A three-dimensional shaft model was developed from the actual geometry and analyzed under four conditions: (K1) an intact shaft, (K2) a shaft with localized journal wear (50–60% of the circumference, maximum depth of 4 mm), (K3) a shaft repaired using Belzona 1111, and (K4) a shaft repaired by machining and installing an SS410 stainless-steel shock sleeve. The original shaft material was modeled as AISI 1030 steel because it represents the actual shaft material used in the turbine. Belzona 1111 was selected as a widely applied polymer composite repair material, whereas SS410 stainless steel was chosen for its mechanical properties, wear resistance, and stiffness, which closely match those of AISI 1030.

The simulation workflow included geometry import, material assignment, mesh generation, application of bearing constraints and operational loads, followed by static structural and modal analyses. Mesh convergence and critical speed validation were conducted before the main simulations to ensure numerical accuracy. Repair effectiveness was assessed by comparing radial deformation, natural frequencies, mode shapes, and deformation symmetry with those of the intact shaft. The most effective repair method was identified as the one that most closely restored the original structural and dynamic behavior while minimizing shaft eccentricity.

Finally, the four shaft conditions were compared in terms of maximum radial deformation, natural frequencies, lateral mode characteristics, mode shapes, and deformation symmetry relative to the baseline condition. The most effective repair method was identified as the alternative that produced the closest dynamic response to the intact shaft while minimizing eccentricity and restoring structural stability, thereby improving the operational reliability of the Kaplan turbine shaft at Wonogiri Hydropower Plant Unit 2.

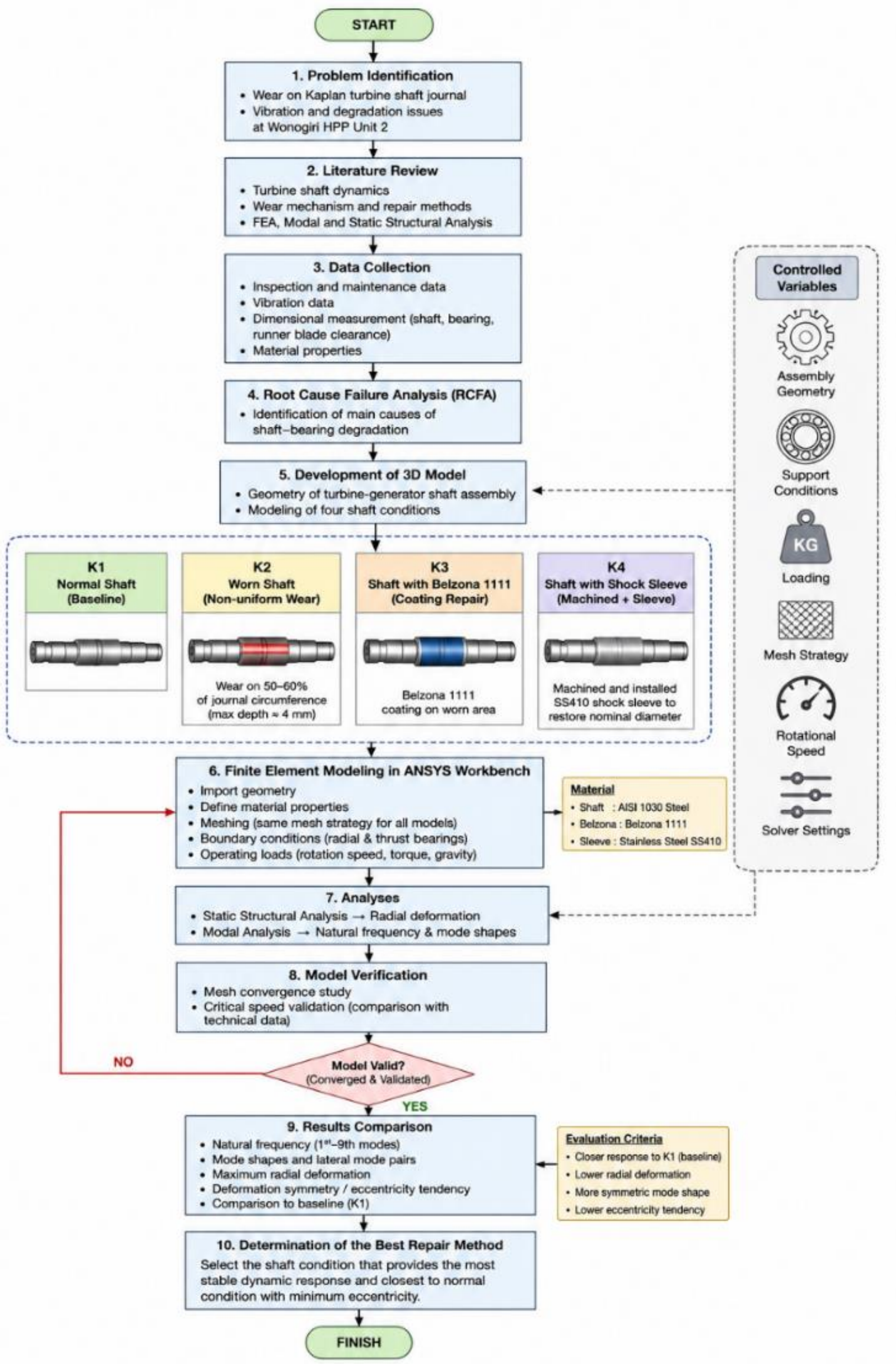

Figure 2. Flow Diagram

3.Results and Discussion

The reliability of the finite element model was verified through mesh convergence analysis and critical speed validation prior to the main simulations. In the static structural analysis, the maximum radial deformation converged at a mesh consisting of 7,354,203 elements, with a deviation of only 1.67% compared with the finer mesh. Similarly, the modal analysis reached mesh independence using 797,789 elements, yielding a deformation difference of 0.64% relative to the denser mesh. These results indicate that the numerical solution was independent of mesh density while maintaining reasonable computational efficiency, as shown in **Figure 2**. Furthermore, validation against the technical critical speed demonstrated good agreement between the numerical model (212.82 rad/s) and the measured value (232.13 rad/s), resulting in an error of only 8.32%. This level of accuracy confirms that the developed finite element model is sufficiently reliable for evaluating the structural and dynamic behavior of the Kaplan turbine shaft under different repair conditions.

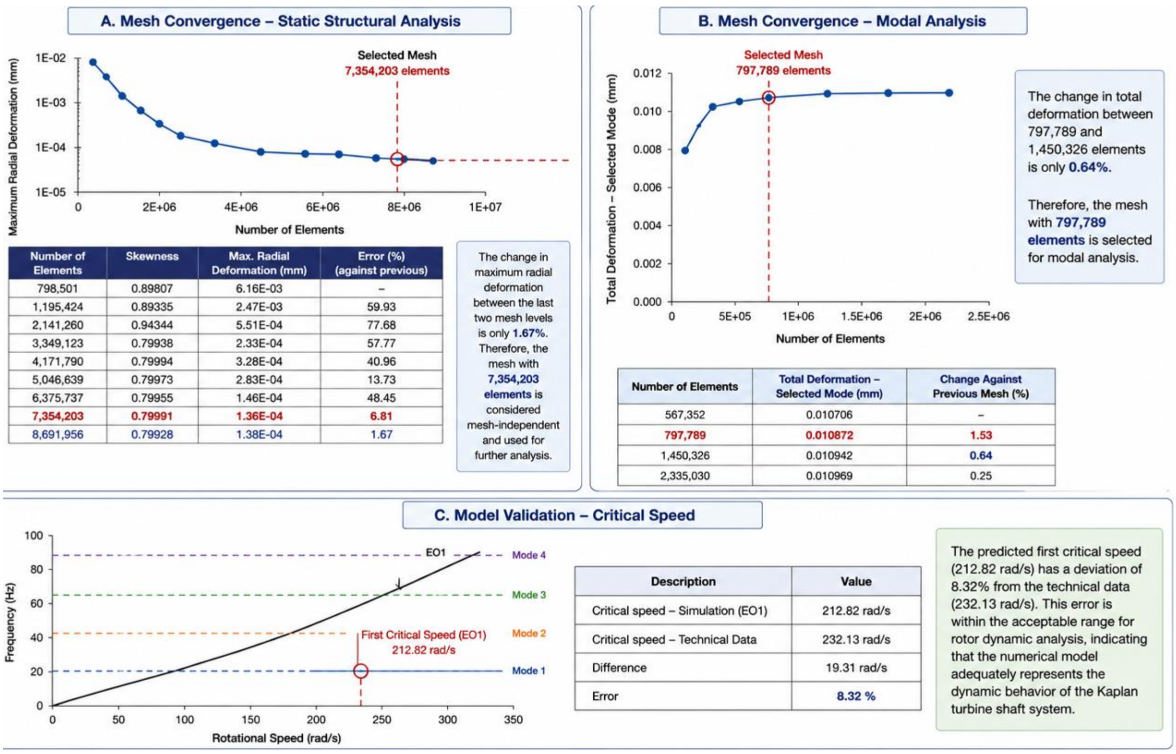

Figure 2. Diagram Numerical Model Verification

The finite element model was verified through mesh convergence analysis and critical speed validation prior to the structural and dynamic simulations. The mesh convergence study demonstrated that the static structural solution became mesh-independent at 7,354,203 elements, with a deviation of only 1.67% compared with the finest mesh. Similarly, the modal analysis reached a stable solution at 797,789 elements, where the variation in total deformation relative to the finer mesh was only 0.64%. These results indicate that the selected mesh densities provide sufficient numerical accuracy while maintaining computational efficiency. Furthermore, the predicted first critical speed (212.82 rad/s) differed by only 8.32% from the technical data (232.13 rad/s), confirming that the developed finite element model adequately represents the dynamic characteristics of the Kaplan turbine shaft.

The verification results are consistent with previous studies that emphasized the importance of mesh-independent finite element solutions in structural analyses. Arini and Pradana (2021) [3] reported that numerical convergence is essential to ensure that predicted deformation is governed by the physical behavior of the structure rather than by mesh discretization. Similarly, Budiman et al. (2021) [4] demonstrated that appropriate mesh refinement significantly improves the accuracy of stress and safety factor predictions in mechanical components [6], [5], [7]. Although these studies focused on different engineering applications, they highlight the same fundamental principle that reliable finite element analyses require adequate mesh convergence before interpreting simulation results [8], [9], [10].

The agreement between the simulated and reference critical speeds also supports the validity of the developed numerical model for rotor dynamic analysis. According to Momčilović et al. (2012) [8] and Urquiza et al. (2014) [11], accurate prediction of the critical speed is essential for evaluating the structural integrity and operational reliability of hydraulic turbine shafts because excessive deviation may indicate inaccurate representations of shaft stiffness, boundary conditions, or bearing support. The prediction error of 8.32% obtained in this study remains within an acceptable engineering range, indicating that the adopted assumptions reasonably represent the actual shaft–bearing system.

Furthermore, the validated numerical model provides a reliable basis for evaluating different shaft repair methods. This finding is in agreement with Cai et al. (2025) [5], who demonstrated that validated finite element models can effectively predict the structural reliability of rotating shaft systems under various operating conditions. Therefore, the verified model developed in this study is considered sufficiently accurate for assessing the influence of wear and repair methods on the structural and dynamic performance of the Kaplan turbine shaft.

The static structural analysis revealed significant differences in radial deformation among the four shaft conditions, as shown in **Figure 3**. As expected, the intact shaft (K1) exhibited the smallest radial deformation (0.000136 mm), indicating a uniform stiffness distribution and a concentric rotor system. In contrast, the worn shaft (K2) experienced the highest deformation (0.033123 mm), representing an increase of approximately 24,255% relative to the baseline condition. The substantial increase resulted from localized material loss, which reduced shaft stiffness and generated an asymmetric mass distribution, thereby increasing shaft eccentricity and lateral deflection. Repair using Belzona 1111 (K3) reduced the maximum deformation to 0.021123 mm, corresponding to a 36.23% reduction compared with the worn shaft. However, the repaired region still exhibited localized deformation because the elastic modulus of Belzona is considerably lower than that of the original steel shaft. Conversely, the SS410 shock sleeve (K4) demonstrated the most favorable structural performance, reducing the maximum radial deformation to 0.00076983 mm, equivalent to a 97.68% reduction relative to K2. The machining process combined with the installation of a stainless-steel sleeve successfully restored shaft geometry, improved stiffness uniformity, and produced a deformation pattern closely resembling the intact shaft. These findings indicate that restoring both the shaft geometry and mechanical properties is essential for minimizing eccentric deformation and improving rotor stability.

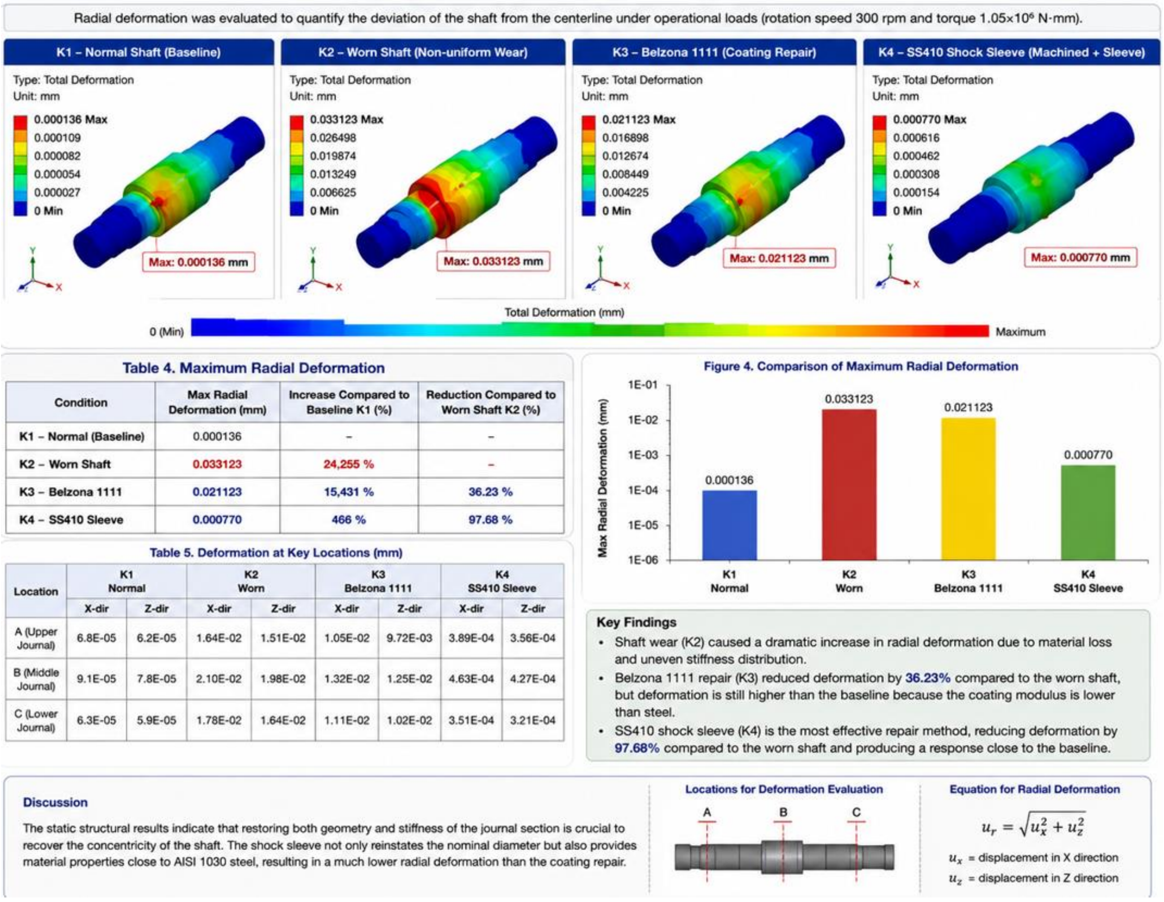

Table 4. Maximum Radial Deformation

Condition	Max Radial Deformation (mm)	Increase Compared to Baseline K1 (%)	Reduction Compared to Worn Shaft K2 (%)
K1 – Normal (Baseline)	0.000136	–	–
K2 – Worn Shaft	0.033123	24,255 %	–
K3 – Belzona 1111	0.021123	15,431 %	36.23 %
K4 – SS410 Sleeve	0.000770	466 %	97.68 %

Table 5. Deformation at Key Locations (mm)

Location	K1 Normal		K2 Worn		K3 Belzona 1111		K4 SS410 Sleeve	
	X-dir	Z-dir	X-dir	Z-dir	X-dir	Z-dir	X-dir	Z-dir
A (Upper Journal)	6.8E-05	6.2E-05	1.64E-02	1.51E-02	1.05E-02	9.72E-03	3.89E-04	3.56E-04
B (Middle Journal)	9.1E-05	7.8E-05	2.10E-02	1.98E-02	1.32E-02	1.25E-02	4.63E-04	4.27E-04
C (Lower Journal)	6.3E-05	5.9E-05	1.78E-02	1.64E-02	1.11E-02	1.02E-02	3.51E-04	3.21E-04

Figure 3. Static Structural Analysis

The static structural analysis confirmed that non-uniform shaft wear significantly increased radial deformation by reducing the shaft cross-sectional area and structural stiffness. This behavior is consistent with the mechanics of materials theory proposed by Hibbeler (2014) [6], which states that structural deformation is governed by material stiffness and cross-sectional geometry. A reduction in shaft stiffness increases elastic deformation under the same loading conditions. The static structural analysis confirmed that non-uniform shaft wear significantly increased radial deformation by reducing the shaft cross-sectional area and structural stiffness. This observation is further supported by Linawati et al. (2019) [7], who reported that the stiffness of a material strongly influences its deformation response under external loading. Although their study focused on geotechnical materials, the same mechanical principle applies to engineering structures, where higher stiffness results in lower deformation.

The findings are consistent with those reported by Momčilović et al. (2012) [8] and Urquiza et al. (2014) [11], who showed that localized wear in hydraulic turbine shafts disrupts load distribution, promotes shaft eccentricity, and reduces structural integrity. The present results further demonstrate that restoring the original shaft geometry and stiffness is essential for recovering structural performance.

Among the evaluated repair methods, the SS410 shock sleeve exhibited the best structural response because its mechanical properties are closer to those of the original shaft material than those of Belzona 1111. This observation agrees with Cai et al. (2025) [5], who emphasized that preserving the original stiffness of rotating shafts is critical for maintaining structural reliability. Likewise, Ridha et al. (2023) [10] highlighted that effective Kaplan turbine repairs should restore both dimensional accuracy and mechanical properties. The finite element approach adopted in this study also supports the findings of Budiman et al. (2021) [4], confirming that numerical simulation is an effective tool for evaluating repair alternatives before field implementation.

Overall, the results indicate that successful shaft restoration depends not only on recovering the original geometry but also on selecting a repair material with mechanical properties comparable to those of the original shaft to ensure structural stability and long-term reliability.

The modal analysis showed that the global vibration characteristics of the shaft assembly were only slightly affected by local wear and repair because the overall mass and stiffness of the rotor system remained largely unchanged. The maximum natural frequency deviation was 0.110% for the worn shaft (K2), 0.418% for the Belzona repair (K3), and only 0.028% for the SS410 shock sleeve (K4) compared with the baseline shaft. Although these frequency shifts were relatively small, the corresponding mode shapes revealed noticeable differences in deformation symmetry. The intact shaft exhibited well-defined orthogonal bending mode pairs, reflecting a balanced mass and stiffness distribution. The worn shaft displayed asymmetric mode shapes caused by uneven stiffness around the journal region, while the Belzona repair partially restored the shaft geometry but still produced localized stiffness discontinuities due to the lower elastic modulus of the repair material. In contrast, the SS410 shock sleeve generated mode shapes and paired natural frequencies that closely matched those of the intact shaft, indicating a more effective restoration of the rotor dynamic characteristics. Therefore, mode shape symmetry provides a more sensitive indicator of repair quality than natural frequency alone.

A comprehensive comparison of the four shaft conditions demonstrated that shaft wear significantly deteriorated both the structural and dynamic performance of the rotor system. The worn shaft exhibited the largest radial deformation, the most asymmetric deformation pattern, and the greatest tendency toward eccentric rotation. Although the Belzona repair improved the shaft geometry and reduced deformation, its lower material stiffness prevented complete recovery of the original dynamic characteristics. The SS410 shock sleeve consistently produced the best overall performance by minimizing radial deformation, maintaining natural frequencies close to the baseline condition, and restoring symmetric mode shapes. The superior performance of the sleeve can be attributed to its mechanical properties, which are more comparable to those of the original AISI 1030 shaft, thereby restoring both the mass distribution and structural stiffness. Consequently, the SS410 shock sleeve is recommended as the most effective repair method for worn Kaplan turbine shafts because it provides the closest structural and dynamic response to the original shaft condition.

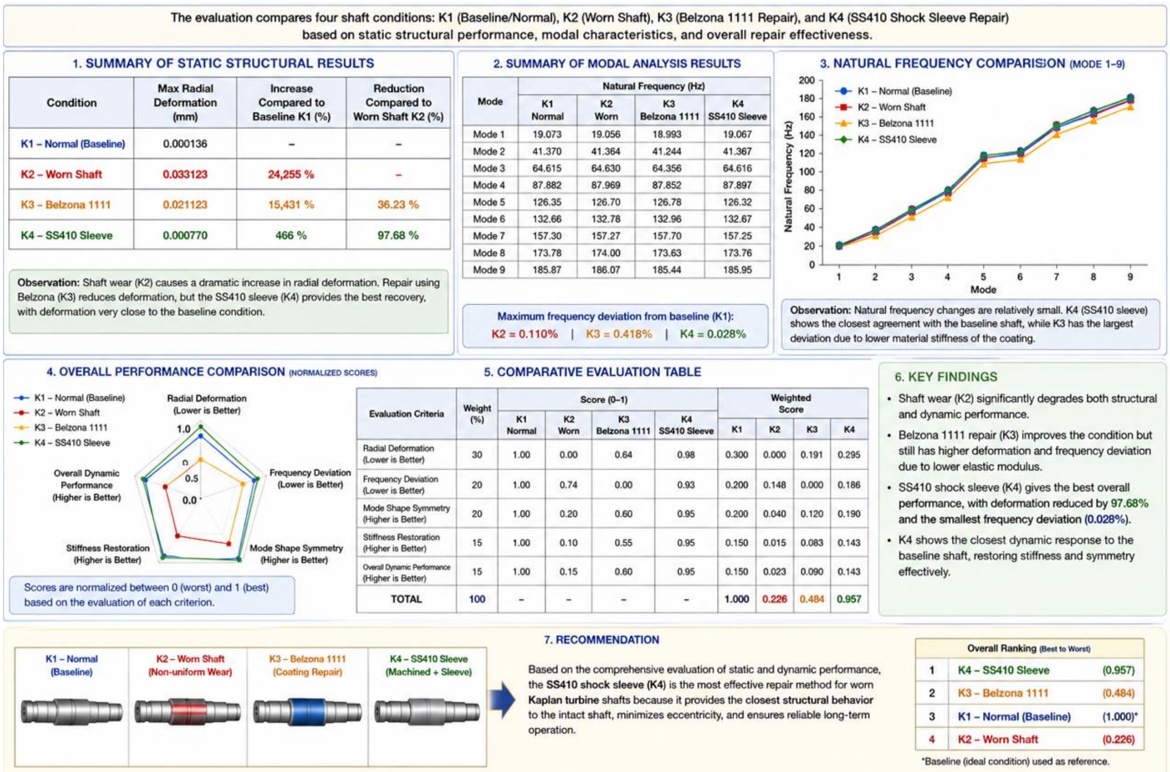

Figure 4. Comparative Evaluation of Repair Methods

The comparative evaluation demonstrates that the repair method substantially influences the structural and dynamic performance of the Kaplan turbine shaft, as shown in **Figure 4**. Among the four investigated conditions, the SS410 shock sleeve (K4) exhibited the best overall performance, characterized by the lowest radial deformation, the smallest natural frequency deviation, and the most symmetric mode shapes. In contrast, the worn shaft (K2) produced the largest radial deformation and the highest degree of eccentricity, while the Belzona repair (K3) provided only partial improvement. These findings indicate that restoring both the shaft geometry and its mechanical properties is essential for recovering the original rotor behavior.

The present results are consistent with the mechanics of materials theory proposed by Hibbeler (2014) [6], which states that the stiffness of a structural component is governed by both its material properties and cross-sectional geometry. Although the Belzona coating successfully restored the journal dimensions, its lower elastic modulus compared with AISI 1030 steel resulted in lower local stiffness and consequently higher radial deformation than the metallic sleeve repair. Conversely, the SS410 shock sleeve restored not only the shaft dimensions but also the structural stiffness, leading to a dynamic response that closely resembled the intact shaft.

These findings are also in agreement with the hydraulic turbine failure investigations conducted by Momčilović et al. (2012) [8] and Urquiza et al. (2014) [11]. Both studies reported that localized shaft degradation alters stress distribution and rotor alignment, ultimately increasing vibration and reducing operational reliability. They emphasized that repair strategies capable of restoring shaft concentricity and stiffness are more effective in preventing recurring failures than repairs that only recover the damaged surface. Similarly, the present study demonstrates that the SS410 sleeve achieved a 97.68% reduction in radial deformation relative to the worn shaft, whereas the Belzona repair reduced deformation by only 36.23%, indicating that the restoration of structural stiffness plays a decisive role in improving shaft performance.

The superior performance of the SS410 shock sleeve is further supported by the reliability analysis presented by Cai et al. (2025) [5], who showed that maintaining an appropriate balance between shaft stiffness and mass distribution is fundamental to preserving the structural reliability of rotating machinery. The minimal natural frequency deviation observed in K4 (0.028%) confirms that the metallic sleeve effectively restored the mass–stiffness ratio of the shaft, whereas the Belzona repair exhibited the largest frequency deviation (0.418%) because of the lower stiffness of the polymer composite. These findings suggest that the mechanical compatibility of the repair material with the original shaft is an important consideration in repair design.

Furthermore, the present results support the observations of Ridha et al. (2023) [10], who highlighted that long-term reliability of Kaplan turbine components depends not only on restoring dimensional accuracy but also on preserving the mechanical characteristics of critical rotating components. The finite element approach adopted in this study also corroborates the work of Budiman et al. (2021) [4], demonstrating that numerical simulation provides an effective engineering tool for quantitatively comparing alternative repair strategies before field implementation.

Overall, this study extends previous research by providing a comprehensive comparison of two practical repair methods based on both static structural and modal analyses. Unlike earlier studies that primarily focused on shaft failure mechanisms or stress analysis, the present work integrates structural deformation, natural frequencies, and mode shape characteristics to evaluate repair effectiveness. This integrated approach provides a more robust engineering basis for selecting repair methods capable of restoring shaft concentricity, minimizing dynamic instability, and improving the long-term reliability of Kaplan turbine shaft systems.

4. Conclusion

This study successfully developed and validated a finite element model to evaluate the structural and dynamic behavior of a worn vertical Kaplan turbine shaft and to compare two practical repair methods. The numerical model demonstrated satisfactory accuracy, with mesh convergence deviations below 2% and a critical speed prediction error of 8.32%, confirming its suitability for structural and modal analyses. The results showed that non-uniform journal wear significantly reduced shaft stiffness, leading to a substantial increase in radial deformation and a greater tendency toward shaft eccentricity. Although the changes in natural frequencies were relatively small, the wear noticeably affected the symmetry of the mode shapes, indicating degradation of the rotor's dynamic behavior. Among the evaluated repair methods, machining followed by the installation of an SS410 stainless-steel shock sleeve provided the best structural and dynamic performance.

This method reduced radial deformation by 97.68% compared with the worn shaft, restored the natural frequencies to values very close to the intact condition, and produced the most symmetrical mode shapes. In contrast, the Belzona 1111 repair improved shaft performance but was less effective because its lower elastic modulus could not fully recover the original structural stiffness. Overall, the findings demonstrate that effective shaft restoration depends not only on recovering the original geometry but also on selecting a repair material with mechanical properties comparable to those of the original shaft. The integrated evaluation using static structural and modal analyses provides a reliable engineering basis for selecting repair strategies that improve the structural integrity, dynamic stability, and long-term reliability of Kaplan turbine shaft systems.

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Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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Availability of data and materials - All data is available from the authors.

Competing interests - The authors declare no competing interest.

Additional information - No additional information from the authors.

References

[1] [1] K. Al Ichlas Imran, "Simulasi Tegangan Von Mises dan Analisa Safety Factor Gantry Crane Kapasitas 3 Ton," Undergraduate Thesis, Universitas Hasanuddin, Makassar, Indonesia, 2017.

[2] American Society of Civil Engineers, Minimum Design Loads for Buildings and Other Structures, 2nd ed. Reston, VA, USA: ASCE, 2003.

[3] R. N. Arini and R. Pradana, "Analisa regangan pada balok dengan menggunakan software Abaqus CAE V6.14," Artesis, vol. 1, no. 2, pp. 193–198, 2021.

[4] F. A. Budiman, A. Septiyanto, A. D. N. I. M. Sudiyono, and R. Setiadi, "Analisis tegangan von Mises dan safety factor pada chassis kendaraan listrik tipe in-wheel," J. Rekayasa Mesin, vol. 16, no. 1, pp. 100–108, 2021.

[5] L. Cai, Z. Jiao, D. Qi, X. Ding, Y. Xu, and Y. Long, "Reliability analysis of impeller and shaft system in shaft-sealed reactor coolant pump," Ann. Nucl. Energy, vol. 226, Art. no. 111884, 2025, doi: https://doi.org/10.1016/j.anucene.2025.111884.

[6] R. C. Hibbeler, Mechanics of Materials, 9th ed. Harlow, U.K.: Pearson Education, 2014.

[7] Linawati, T. Sulistyowati, and I. H. M., "Analisis modulus geser maksimum tanah lempung ekspansif dengan perkuatan serat ijuk berdasarkan metode empiris," Spektrum Sipil, vol. 6, no. 1, pp. 69–78, 2019.

[8] D. Momčilović, Z. Odanović, R. Mitrović, I. Atanasovska, and T. Vuherer, "Failure analysis of hydraulic turbine shaft," Eng. Fail. Anal., vol. 20, pp. 54–66, 2012, doi: https://doi.org/10.1016/j.engfailanal.2011.10.006.

[9] PT PLN Indonesia Power UBP Mrica, Operation and Maintenance Handbook of Wonogiri Hydropower Plant. Banjarnegara, Indonesia: PT PLN Indonesia

Power UBP Mrica, 2025.

[10] W. K. M. Ridha, K. R. Kashyzadeh, and S. Ghorbani, “Common failures in hydraulic Kaplan turbine blades and practical solutions,” Materials, vol. 16, no. 9, Art. no. 3303, 2023, doi: https://doi.org/10.3390/ma16093303.

[11] G. Urquiza, J. C. García, J. G. González, L. Castro, J. A. Rodríguez, M. A. Basurto-Pensado, and O. F. Mendoza, “Failure analysis of a hydraulic Kaplan turbine shaft,” Eng. Fail. Anal., vol. 41, pp. 108–117, 2014, doi: https://doi.org/10.1016/j.engfailanal.2014.02.011.