Repair of Cracked 150 MW High-Pressure Steam Turbine Rotor Coupling

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Abstract. A 150 MW high-pressure steam turbine rotor in Philippine experienced cracking in coupling area. The root cause of crack failure was investigated, and it was revealed that alignment setup design from original equipment manufacturer (OEM) contributed to the failure. The cracked coupling was restored by weld build up back to original dimension and new alignment target was recalculated and the result was counterchecked by finite element analysis (FEA) method to verify the stress level reduction.

1. Background
A power plant in Philippine was having continuous vibration issue on one of their unit during the operation and vibration analysis that was performed by plant engineer indicated that there was indication of crack in the rotor. The plant then pulled the HIP and LP rotor for further investigation when NDT inspection in HIP rotor coupling face reveal a longitudinal crack across the coupling area. Figure 1 below represents the general train arrangement of the unit. The train consists of HIP rotor, LP rotor and generator. Two bearings support the HIP rotor: #1 (journal) and #2 (combined journal-thrust bearing), and the LP rotor is supported by bearings #2 and #3 (journal). Generator rests on two journal bearings, #4 and #5.

Figure 1. Steam Turbine – Generator Train Arrangement
1.1. Initial Finding
The coupling condition of the HIP rotor have an extensive crack across the coupling face, exceeding API 687 NDT acceptance criteria [1], visually the crack can be seen in below figure 2.

![Figure 2. Showing crack condition on HIP rotor coupling](image)

2. Repair Methodology
The initial assessment was done and recommend the coupling to be repaired by weld repair as the method to restore the coupling to original condition. Beside coupling restoration, original alignment target was deemed too excessive and might contribute to initiation of crack. New alignment target was developed based on the thermal growth calculation and the stress level before and after alignment adjustment was analyzed using FEA method.

3. Weld Repair Plan
The proposed plan for weld repair in general can be seen in below major point:

- Coupling undercut
- Weld Build-up Coupling [2][3]
- Post Weld Heat Treatment [2][3]
- Final Machining

3.1. Undercut the original coupling
For reconstruction of the coupling area, all dimension was first measured, and reverse engineered. This data will be used to reconstruct the final dimension of the coupling after welding.

The undercut was designed so that all heat affected zone (HAZ) was placed in low stress area near the coupling [4]. Some detail of final drawing can be seen in below figure 3.
3.2. **Weld Repair and PWHT**

After the undercut drawing was developed, the coupling was machined, and weld repair afterward as can be seen in below figure 4.

![Figure 4](image)

**Figure 4.** (a) Machining to remove cracked coupling; (b) weld build up process; (c) as-welded coupling

3.3. **Final Machining**

After all criteria for welding acceptance was fulfilled, the coupling was final machined to original dimension as per initial reverse engineering data. Below is the detail of this process.
4. Alignment Assessment

The original OEM procedure defines the LP rotor to Generator coupling to have zero offset and angular misalignment, while the HIP rotor has to be setup 0.24 mm higher than the LP rotor and HIP to LP coupling to have 0.33 mm opening at the bottom. The OEM modified the opening at the bottom to 0.29 – 0.30 mm, visualization can be seen in below figure:

Figure 6. Alignment Targets defined by the OEM

Based on engineering assessment, the alignment target was to excessive, combination of high stress level on the coupling and torque load was deemed the major contribution to crack initiation. New alignment target was proposed so that the load on the coupling was decrease while maintain the concentricity of all shaft centerline during full load condition.

4.1. New Alignment Target

When calculating alignment targets, the following main factors should be taken into account:

- Thermal growth of the case pedestals in the locations of the bearing journals.
- Initial sag of the rotors.
- Static loading of the bearings during operation.
4.2. Thermal Growth Calculations

The temperatures of the bearing pedestals were measured from the sister unit operating at the power plant. The sister unit was warmed up and operating with full load at the time when these measurements were taken. Table 1 contains the input data and resulting calculations of the turbine and generator support’s vertical thermal growth. LIT is the temperature difference between ambient conditions (20 °C) and average operating temperature at the corresponding locations. The assumed coefficient of thermal expansion for all pedestal components for this calculation was \(11 \times 10^{-6}\) mm/mm·°C (steel).

| Bearing # | Position                        | Avg. Temp. | LIT | Vert. distance to C/L | Vert. growth ABS | Vert. growth REL | Rotor Axial Length | Axial Position |
|----------|---------------------------------|------------|-----|-----------------------|-----------------|-----------------|--------------------|----------------|
|          | Front stand (HP)                | 65         | 45  | 900                   | 0.446           | 0.198           | 0                  | 0              |
|          | Mid stand (IP)                  | 50         | 30  | 900                   | 0.297           | 0.050           | 5949               | 5949           |
|          | LP - GEN End                    | 50         | 30  | 900                   | 0.297           | 0.050           | 5060               | 11009          |
|          | GEN – Turbine end               | 45         | 25  | 900                   | 0.248           | 0.000           | 7870               | 11009          |
|          | GEN – Exciter end               | 45         | 25  | 900                   | 0.248           | 0.000           | 7870               | 18879          |

Figure 7 shows the plot of calculated relative thermal growth for the temperatures assumed in table 1.

![Figure 7. Relative Vertical Thermal Growth of the Rotors](image)

The temperature difference between LP turbine rotor and generator rotor is found to be insignificant. The amount of misalignment required in the cold conditions between the LP coupling and the generator rotor is within the alignment tolerance attainable for the train. Therefore, no offset and no gap are required in these locations during the cold alignment.

4.3. Rotors Sag

The OEM Rotor sag for HIP and LP rotors is shown in see Figure 8 and Figure 9. Based on this data, the HIP rotor in static position is deflected 0.1 mm higher than the centerline at the LP coupling. The
LP rotor in static position is approximately 0.08 mm higher than the centerline at the LP-generator coupling (LP generator end).

The sag is expected to reduce after the rotors are have gone through a slow roll process and ready to run at the operating speed and temperature.

![Figure 8. HIP Rotor Sag](image1)

![Figure 9. LP Rotor Sag](image2)

4.4. Rotor-dynamic Considerations

The OEM installation procedure for the subject unit calls for the following static load distribution between the turbine journal bearings with the recommended elevation changes made to the bearings:

- Bearing #1 = 6874 kg
- Bearing #2 = 16892 kg
- Bearing #3 = 12647 kg

The statement made in the OEM installation procedure about aligning the rotors to unload bearing #2, which carries the heaviest load, has merit. However, it is not believed that the alignment targets proposed by the OEM satisfy this recommendation due to the expectation that the HP front pedestal is going to grow more than the mid-section pedestal. Therefore, the following could happen with the alignment targets proposed by the OEM:

- Front pedestal growth may unload bearing #1 (already lightly loaded by design) and cause instability.
- Relative growth between front and mid pedestals will increase load on bearings #2 and #3
Excessive forces in the HIP to LP rotors coupling joint may lead to coupling damage, as currently observed by the plant.

4.5. Recommended Alignment Targets

The new vertical alignment targets recommended for the unit were defined using the expected thermal growth of the turbine pedestals and initial sag in the rotor. Table 2 and Figure 10 summarize the proposed new alignment targets.

**Table 2. Proposed Cold Alignment Targets**

| Coupling                | Offset, mm | Gap, mm |
|-------------------------|------------|---------|
| HIP to LP Coupling      | 0.00       | 0.10    |
| (open at the top)       |            |         |
| LP to Generator Coupling| 0.00       | 0.00    |

Expected alignment tolerance is ±0.08 mm (±0.003”).

**Figure 10. Proposed Cold Alignment Targets**

5. Coupling Stress Analysis

Stresses in the HIP and LP turbine couplings were analyzed using Finite Element Analysis software (ANSYS). Stress simulations were performed for two cases: alignment targets proposed by the OEM, and new proposed alignment targets proposed. The stresses for both cases were simulated for cold alignment conditions and included bolt pretensions. No rotational or thermal stresses were taken into account, since they are assumed to be similar for both cases regardless of the cold alignment.

Figure 11 (a) and (b) show equivalent (Von Mises) stresses in the HIP rotor coupling for the alignment target proposed by the OEM and new setup, respectively. Qualitatively, the maximum stress using new alignment target decrease 60% compared to original OEM alignment. This provides a confirmation that the new proposed alignment for HIP to LP rotor addresses the issue of excessive stresses in the coupling.
Figure 11. (a) OEM Alignment Targets (b) New Alignment Targets - Equivalent Stresses in HIP Rotor Coupling

6. Conclusion
The crack on coupling was repaired using the well proven weld build up method and improve the alignment target so that the coupling has lower stress due to alignment. The rotor was put back into the unit and the result of both the coupling and the alignment adjustment was improved to get more reliable unit.

7. References
[1] API Recommended Practice 687, Rotor Repair, Chapter 1, table 1.8.1
[2] Sulzer Indonesia, May 2013, Welding Procedure Specification QW-482, Sulzer Internal document
[3] Sulzer Indonesia, June 2013, Procedure Qualification Record QW-483, Sulzer Internal document
[4] API Recommended Practice 687, Rotor Repair, Chapter 1, appendix D.2.2.3