Design modifications and repair of a 90MW steam turbine after a catastrophic failure

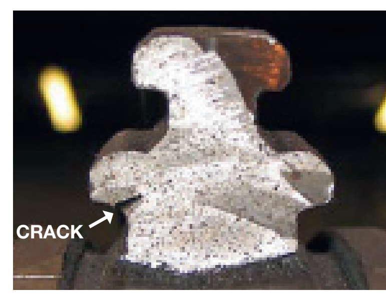
A catastrophic failure of a 90MW steam turbine occurred due to a fracture of the blade root in one of the disks, which, in turn, caused massive damage to the rotating and stationary parts. As cost and delivery of a new replacement rotor were prohibitive to the customer, Sulzer offered more competitive pricing and a shorter delivery than the OEM. Sulzer was therefore contracted to reengineer the blade root geometry and weld repair 6 of the total 12 disks. The entire engineering analysis and repair process was completed in 18 weeks.

The ASTM A470 Class 7 steel T13 stage disk of the turbine's low-pressure integral rotor suffered a catastrophic failure. The low-pressure rotor is of a double-flow design, with the steam inlet at the midspan of the rotor, as shown in figure 1. The failure occurred as a blade separated from the rotor during operation, causing extensive damage to downstream stationary and rotating components along with heavy rubs on the rotor body.

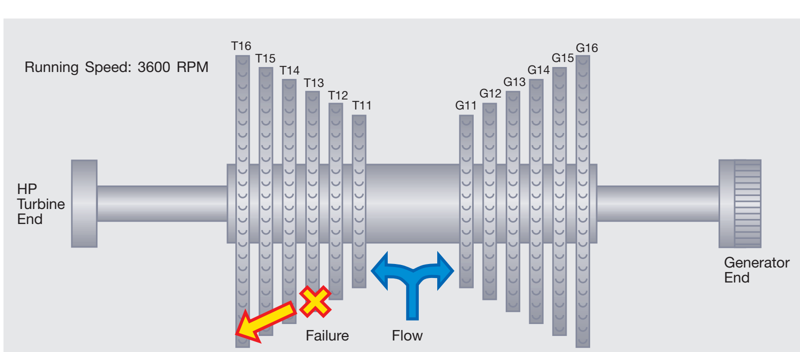
Sulzer Turbo Services was also contracted to provide an engineering solution that would prevent a failure reoccurrence. The main strategy was to redesign the blade root in order to lower the stress concentration on the disk hooks. After the design was finalized, the rotor was repaired by welding the damaged disks. New sets of rotating blades were manufactured and the diaphragms were either repaired or manufactured anew. Other work included minor repairs on the high-pressure rotor, generator, field installation, and startup monitoring of the unit.

The T13 disk failure included cracks in the blade hooks, so, at Sulzer's recommendation, the customer agreed to remove blades from the generator end of the rotor to permit evaluation of those blade roots as well. Throughout the course of the visual and magnetic particle inspections, additional cracks were identified in the T14, T15, G13, G14, and G15 stages. This foresight was crucial, for severe damages would have surely occurred after the machine was reinstalled.

The sections of the T13 and T14 disk had been removed prior to the rotor's arrival at Sulzer. Figure 2 shows the typical crack locations in the corners of the root hooks. Magnetic particle inspections revealed that the cracks ran circumferentially around the entire disk, in both the upper and the lower blade hooks.



2 Typical crack in the blade root (around the entire wheel).

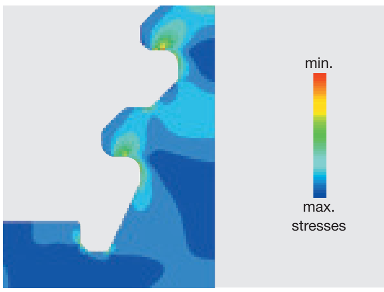


1 Low pressure turbine rotor with symmetrical flow.

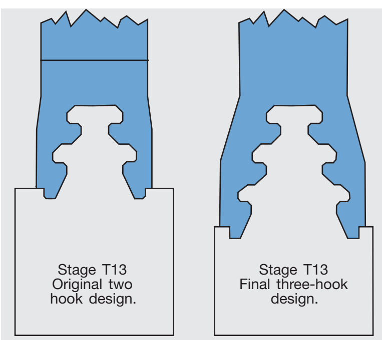
Analysis and design modifications

The primary strategy of the engineering analysis was to evaluate the stress distribution on the original disk design, and then redesign the root profiles in order to reduce the stress magnitudes on the hooks. A major requirement of the redesign was to assure that the geometrical modifications still permitted the rotor to fit properly without casing modifications.

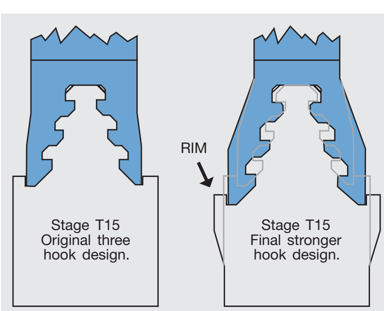
Finite element analysis (FEA) was performed in order to quantify the stress distribution on the disks under normal operating conditions. Although



3 High stresses in the original disk blade roots.



4 Original two blade hooks (left) in stage T13 was increased to three (right), which reduced the stress to 81% of its original value.



5 Final design of stage T15 (right) reduced stresses by almost 50% of the original (left).

the initial disk failure was localized to stage T13, stress distributions for stages T14, T15, G13, G14, and G15 were determined as well. The model geometry was acquired from the actual disk and blade samples and then drawn in a CAD (computer-aided design) program. The CAD models were imported into the finite element solver, from which stress distributions were calculated 3.

Figure 4 shows the final design of the failed T13 row. This design reduced the stress to 81% of its original value. The same engineering reviews were also performed for the larger stage T15. After several iterations, a root design for T15 was achieved that would reduce the stress magnitudes by almost 50% of their original values 5. However, the final design did not fit within the envelope of the original disk geometry, so a portion of the disk was then widened to keep the outside loading rim in proportion to its original configuration. The original clearance of the stationary components was kept intact by relocating the diaphragms.

Stress magnitudes were also reduced through the use of generous, elliptical fillet radii instead of the standard straight fillets as shown in figure 6. A more generous fillet helps distribute the stress, decreasing the incidence of high localized stress magnitudes and lowering the generalized stress magnitudes.

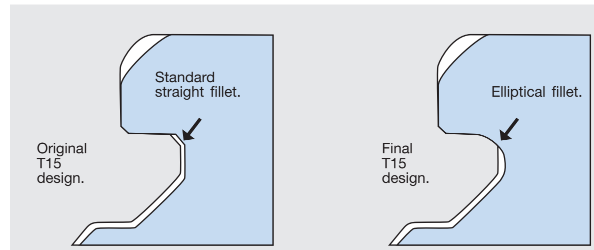
Anatomy of the weld repair

As part of the weld preparation process, the damaged sections of the disk were cut from the rotor. The FEA from the engineering analysis determined the radial location of the cuts. Each stage was cut at a diameter where the heat affected zone (HAZ) would be away from any areas of stress concentration.

At the same location of the cut, on either side of the rings, "weld-off" rings were welded in place. These rings helped contain the weld overlay profiles to be used for the reconstruction of the disk. Figure 7 shows stages T12, T14, and T15 being prepared for welding, with weld-off rings partially installed and thermocouples for temperature monitoring.

Welding

The welding method employed was submerged arc. During the procedure, the



6 Stresses also reduced by using elliptical fillets (right) instead of straight fillets (left).

disks had to be preheated and the heat had to be carefully controlled throughout the entire operation in order to achieve proper weld quality. Due to the tight repair schedule, both ends of the rotor were welded simultaneously. Figure 8 shows a detail of the weld overlay.

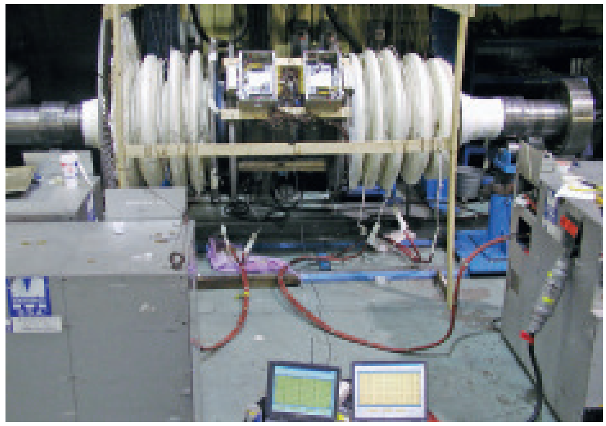
Immediately after the welding was completed, the disks had to be heated for "dehydrogenation," or hydrogen removal. This procedure causes the hydrogen trapped in the weld to migrate to the surface.

Stress relief

The rotor was machined to a stress relief profile. The quality of the weld was then inspected using wet magnetic particle and ultrasonic techniques.

7 Stages T12, T14, and T15 being prepared for welding.

8 Weld overlay detail.



9 Stress relieving in the horizontal position while slowly rolling.

While slowly rolling, the rotor was stress relieved in the horizontal position. Induction heating was used to bring the stress relief areas to the correct temperature. Induction heating maximizes the efficiency of this procedure, since it allows localized treatment of only the areas affected by the welding. It also eliminates the problem of having to stress relieve a rotor of this size vertically in a furnace. The power supplies used for heat induction were controlled via thermocouples located on the disks and data was transmitted wirelessly to a stationary control module as shown in figure 9.

The last steps of the repair procedure were the final machining of the redesigned root profiles, reloading of the blades on the rotor, and balancing 10.

Summary

The shop repair work, which included the weld reconstruction of the forging, the blade manufacturing and installation, and rotor balancing were accomplished in under 18 weeks. This time frame included the engineering analysis which was completed in 4 weeks. It was possible to finish this repair quickly because the weld preparation process was started while the engineering work was still underway. Additionally, welding and induction heating both rotor ends simultaneously provided substantial time savings.

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10 Balancing of the repaired rotor.