Effect of welding pattern during repair and maintenance of Francis runner on sediment erosion: An experimental investigation using RDA

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Abstract. In Nepal, sediment erosion is a major cause of hydro-turbine failure. Every year turbine parts expose to water got eroded and failed ultimately resulting in loss of efficiency as well as increase in the repair cost. For repair of these eroded surfaces welding is quit famous in Nepal due to low cost to build up the eroded surface however specific welding pattern on the eroded surfaces has not been used which results low strength in repaired equipment. In this paper, the study of the relation of the welding pattern on the erosion rate had carried out taking the Francis turbine blade of Dhamile Khola (14 kW) as reference. Experimental analysis was adopted for studying the effect of welding pattern on erosion rate through laboratory tests. Four different welding patterns on four different specimens were developed and accelerated tests were carried out in the Rotating Disc Apparatus (RDA) at Turbine Testing Lab (TTL), Kathmandu University. Furthermore, erosion pattern on forged blades were compared with the CFD analysis carried out on same blade which is similar. After an operation time of 1050 minutes, the extent of wear was found significantly less in the test specimen with right inclined welding pattern taking material loss as a basis for comparison. The aim of this paper is to provide a specific welding pattern with relatively less erosion rate during the repair and maintenance of the sediment eroded surface of the runners.

1. Introduction

1.1. Background

Hydropower plants are the economic source of sustainable energy with its operating duration of 50 to 100 years and turbine design life of 20 years. In Nepal, hydropower plants run in extreme sediment erosive environments due to which the runner material erodes which reduces the efficiency and increases the cost [1]. The erosion damage of turbines of hydropower plants in Himalayan Rivers, in particularly in Nepal is high [2]. Hydraulic turbine components operating in sediment-laden water are subject to abrasive and erosive wear. This wear not only reduces the efficiency and the life of the turbine but also causes problems in operation and maintenance, which ultimately leads to economic losses. This is a global operation and maintenance problem of hydropower plants. The high sediment concentration combined with high percentage of quartz content in water causes severe damage to hydraulic turbine components. Withdrawal of clean water from the river for power production is
expensive due to design, construction and operation of sediment settling basins. Even with the settling basins, 100% removal of fine sediments is impossible and uneconomical [3]. The relation between the sediment erosion, operational challenges and ultimate solution is shown in the figure below.

![Figure 1. Sediment induced operation and maintenance challenge [1].](image1)

However, the ultimate solution to maintain the efficiency and decrease the risk of operation is either replacement with new runner or repair and operation. Weld repair of damaged runner is preferred over replacing the damaged one with a new one due to low cost. Moreover, the welding repair does not impair the material property if carried out properly. Therefore, welding repair is chosen as the best alternative of repair and maintenance of turbines in hydropower plants in Nepal.

In this paper, observation of the sediment erosion pattern in the Francis turbine and erosion rate on Francis blades with different welding pattern was carried out.

![Figure 2. Erosion at outlet of runner.](image2)  ![Figure 3. Welding on eroded joints](image3)

1.2. Current status of research

Study of the effect of sediment erosion in hydraulic turbines is complex. Several researches have been carried out in the field of sediment erosion in hydro turbines focusing on establishing the empirical relations to estimate the effects of sediment erosion in hydraulic turbines and identification of the parameters upon which the erosion rate is dependent. Some studies have been carried out to develop mathematical model to estimate the effect of sediment erosion in different components of the power plant. Some of the researches were focused on reducing the sediment erosion on the turbine runner by optimizing the design of the turbine blades.

But few researches have been done on the repair of the hydro turbines. Nevertheless, a handful research was also carried for the quality control for the repair of Pelton turbines [1], there has been a lack of research for the welding repair of the Francis turbine. The current study is expected to produce results which might help in the welding repair of the Francis turbine.
2. Experiment

2.1 Rotating Disc Apparatus (RDA) Setup
The existing RDA at TTL, KU designed by Oblique Shrestha [4] was revived and necessary maintenance was done. The test setup was designed in such a way that sediment erosion in Francis runner could be easily simulated in laboratory conditions. The setup was introduced with Variable Frequency Drive (VFD), digital temperature sensor, pressure sensor and necessary lubrications was done. The setup has mainly four parts: (a) rotating disc with blade and blade attachments, (b) housing and supporting structures, (c) cover and (d) shaft, belt drive, VFD and motor.

![RDA setup at TTL, KU.](image)

2.2 Test Specimens
Since the main objective of this study was to compare the different welding patterns in the Francis turbine runner blades, test specimens with different welding patterns were fabricated. Specification of 14kW Francis turbine designed for “Dhamile Khola” is taken as the reference for blade. CFD simulations have been carried out to evaluate the hydraulic performance and erosion on blade surface of the blade design and later compared with the wear patterns on the blades after experiment. The basic hydraulic parameters and their values used for design are listed in table below.

| SN | Parameters                  | Value | Unit |
|----|-----------------------------|-------|------|
| 1  | Net design head, H          | 16    | m    |
| 2  | Design flow rate, Q         | 0.1   | m³/s |
| 3  | Runner efficiency, \( \eta \) | 92    | %    |

The blade designs developed in those studies had been used in this study by scaling down to 3:4 ratio. This had been done to accommodate four numbers of blades in the rotating disc of 320 mm diameter. For fabrication of the model blades, both the designs were first modelled into 3D CAD models in Autodesk® Inventor®. The blades were modelled together with blade base for casting as a single block. The 3D CAD models were then printed into plastic models with the help of a 3D printer installed in TTL. The Francis runner blades required as test specimens were forged and machined to bring into shape. The forged blade profiles were welded together with the base to accommodate in the
RDA disc. The test specimen profile was grinded and made smooth with the sandpaper. For the first test four different layer of paints (i.e. red, yellow, green, blue) were coated on the blades. Later the paints were removed Acetone (C3H6O, and specimens were welded at the pressure side with different welding patterns. Figure 5 shows the plastic model, painted test specimens and the final weld repaired test specimen.

![Figure 5. Test specimens preparation (a) 3D printed test specimen (b) Forged and painted blade (c) weld repaired test specimen (d) Grinding and surface finishing.](image)

### 2.3 Welding process.
For this experimental study Shielded Metal Arc Welding (SMAW) was used as to prepare the test specimens. For the welding on the blades, the test specimens were taken to Kathmandu Auto Engineering Pvt. Ltd where welding was performed by professional welders. Welding was performed on the pressure side of the blades as erosion pattern was observed on that side from our first test and previous researches [5]. 50 % weld overlap was done to increase the hardness which increase the erosion resistance of the test specimens [6]. Since reduction in hardness was seen due to deposition of many beads [7], single weld bead was done on the test specimens. After each weld, the slag on the weld bead was removed and the test specimen was left to cool to avoid hole on the test specimens. Annealing was done to remove welding impurities after welding [8]. Grinding/Surface finishing was done after welding. Four different welding patterns were experimented which are shown in figure 6.

![Figure 6. Different welding pattern (a) Vertical welding (b) Left inclined welding (c) Right inclined welding (d) Horizontal welding.](image)

### 3. Experiment Procedure
Experiment was conducted to compare the effect of sediments in four different welding patterns, various parameters common for the test run were set to be constant throughout the experiment [9]. The descriptions of these parameters are listed in Table 2. The test specimens were thoroughly cleaned with detergent solution, dried and weighed before each test runs. The internal surface of the casing and cover was also cleaned. The clean set of test specimens were mounted on the disc.
Table 2. Parameters of laboratory setup.

| Parameters                        | Value                                                                 |
|-----------------------------------|----------------------------------------------------------------------|
| Speed of rotation of motor        | 1100 rpm                                                            |
| Speed of rotation of disc         | 550 rpm (obtained with V-belt drive of pulley ratio 1:2)            |
| Direction of rotation of disc     | Anti-clockwise as viewed from front                                |
| Diameter of disc                  | 350 mm                                                              |
| Radius of mounting of specimen    | 140 mm                                                              |
| Volume of water in casing         | 9.17 ltrs                                                           |
| Specimens used                    | H1 = Blade 1 with horizontal welding pattern                        |
|                                  | V2 = Blade 2 with vertical welding pattern                          |
|                                  | R3 = Blade 3 with right inclined welding pattern                    |
|                                  | L4 = Blade 4 with left inclined welding pattern                     |
| Material of specimen              | Stainless steel                                                     |
| Number of specimen                | 4                                                                   |
| Operating time                    | 120 minutes                                                         |
| Total number of observations      | 10                                                                  |
| Water                             | Used from the water supply of TTL                                   |
| Sediment concentration            | 66,250 ppm                                                          |
| Sediment used                     | Sunkoshi river                                                      |
| Sediment particle size            | 75 to 200 micron                                                    |
| Thermometer                       | Digital type                                                        |
| Pressure Gauge                    | Glycerin Filled Pressure Guage, Range 0 to 60 psi                   |
| Weight balance                    | Electronic weighing machine, max. 200 gm, least count 0.1 mg.        |
| Welding rod                       | E6013                                                               |

Figure 7 shows the mechanism of mounting of test specimens on the disc. Each test specimen consisted of a blade and a circular plate called blade base. The test specimen was mounted in the disc with the help of the blade base. The disc had four circular seats where the blade base fitted perfectly as shown in figure 7. Each test specimen was attached to the disc with the help of circular head screw and nut. The holes in the blade base for mounting screws had been drilled in such a way that the angle of relative velocity of water at the leading edge of the test specimen was 16.8°. In case of real turbines, this angle depends upon the opening of the guide vanes.

![Figure 7. Mounting procedure of test specimen on disc.](image.png)

The disc was mounted on the shaft and tightened with the help of luck nut. After the cover of the housing was closed and the nut and bolts were tightened securely, the casing was filled with a mixture of sand and water at required concentration, and the test run was started. After running the apparatus for predefined period, the motor was stopped and the slurry mixture inside the casing was drained out by opening the drain plug. The disc was removed from the shaft; the test specimens were removed from the disc, and washed thoroughly with detergent and clean water. The weight loss measurements
were taken with the help of the Electronic weighing machine as specified in the Table 2. The weight loss was calculated by noting down the difference between the weight of the test specimens before and after each test run. The photographs of the surface of specimens were also recorded to observe the pattern of wear being developed after each test run. The patterns of erosion on the surface of test specimens were also observed with the help of painted surface. This was done to quickly identify the location of wear in the blade surface. The test specimens were spray painted to obtain smooth paint surface and dried for about 24 hours before the test. The specimens were then mounted on the disc and the apparatus was run for an hour to observe the removal of paint from the blade surface. The test pieces were taken out of the apparatus, cleaned and dried thoroughly. Photographs were taken and compared with the photographs taken prior to running the test.

4. Observations and Discussion

4.1 Flow pattern around the blades

CFD analysis of the sediment erosion and cavitation on 14 KW Francis runner of Dhamile Khola to observe the wear pattern on the Francis blade profile was done by other researchers [10]. The results from the simulations are shown in figure 8. The highest erosion was predicted at the outlet blade surface than other components of the turbine as relative velocity is more at the outlet regions of the runner. Because of the high relative velocity, most of the particles will move towards the outlet diameter in the runner outlet and hence more effect of erosion was observed. These simulations also reflect that the outlet area of pressure side of the runner is highly exposed to erosion which show the erosion patterns on runner blade at shroud portions by erosion rate density. Furthermore, erosion at the outlet of suction side near shroud region was observed.

![Figure 8. CFD results [10] (a) wear on pressure side (b) wear on suction side.](image)

4.2 Pattern of Erosion

![Figure 9. Wear pattern on pressure side from experimental test.](image)
Blades with the painted region were observed step-by-step with every test run for eroded surface. The erosion of paint specimens has been observed mostly in the inlet edge, near the shroud and the outlet region of the blade surface. The removal of paint in the inlet region might have occurred due to secondary flow vortex erosion. Similarly, the removal of paint in the outlet region of pressure side might have occurred due to micro erosion. The erosion pattern near the shroud region of the pressure side might have been because of the incorrect stagnation of the test specimens and due to the impair blade profile.

The removal of paint near the base was due to the vortex created by the bolt head. The four layers of paint were completely removed at the inlet and shroud region of the pressure side. As we go a little further from inlet towards the outlet, yellow paint was seen (green and blue color were removed from the blade). As we go more towards the outlet region, minor traces of paint removal were seen.

The wear has been observed in the suction side of the test specimens. The erosion is mostly observed in extreme outlet region of the blade close to shroud. The wear pattern on the suction side at the outlet of near the shroud that may be of turbine operating on low head experience swirl vortex due to low pressure created on the suction side unsupported by draft tube.

4.3 Loss of material

The recorded weights of all of the four test specimens are shown in figure 11 with respect to the duration of test run. The figure 11 shows that the total weight loss in test specimen R3 is quite lesser than that the other test specimens.

The figure 11 shows that the rate of decrease in the weight of R3 is slightly lesser than other test specimens. This indicates that, if this rate of erosion continues for longer duration of operating time, the amount of weight loss in the test specimen R3 will be significantly lesser than that in the other test specimens.

The sand particle used in the experiment as erodent remain inside the system throughout a single test which is quite different from the real case where fresh sediment particles strike the blade surface continuously. As the introduced erodent keep striking the blade surface for entire duration of test, the erodent property is degraded due to particle degradation. The effect of this degradation has not been considered while calculating the amount of material loss in the test specimens, which suggests that the loss of material in the turbine of real cases is higher than that observed in this study.

The amount of erosion in the test specimens is analysed in terms of cumulative erosion in all the welding patterns. The cumulative erosion gives a picture of total erosion occurring in the specimens after each test run. It can also be defined as the ratio of total weight loss in the specimens from the beginning of the experiment to the original weight of the test pieces at the beginning, and expressed as weight loss in milligram per gram of test specimen. Equation (1) gives the cumulative erosion in the test pieces.
\[ e_i = \frac{(w_o - w_i)}{w_o} \times 100 \text{ [mg/gm]} \quad (1) \]

**Figure 11.** Recorded weights of the test specimens after each test.

Figure 12 shows the graphical representation of the cumulative erosion in the test pieces. The total erosion in the test specimens H1, V2, R3 and L4 after the operation of 1050 minutes are 2.87 mg/gm, 2.55 mg/gm, 2.51 mg/gm and 3.02 mg/gm respectively. This implies that the erosion in R3 (Right inclined welding pattern) is considerably lesser than that of other test specimens. The graph also shows that the amount of erosion is increasing with the time of exposure of test specimens to sediments. It is obvious, as the damaged surface of blades will further accelerate the erosion rate as it disturbs the flow of water.

**Figure 12.** Cumulative erosion in test specimens.
The difference in erosion has also been analysed in terms of percentage difference, which is shown in Table 4. This quantity can be termed as the reduction in amount of erosion, which is achieved if one welding pattern is used instead of the other. The reduction in erosion is calculated using eq. (2).

\[
\text{Reduction in erosion} = \frac{(e_A - e_B)}{e_A} \times 100\% \tag{2}
\]

| SN | Test Duration (min) | Reduction in erosion (%) | L4 vs H1 | H1 vs V2 | V2 vs R3 |
|----|---------------------|---------------------------|----------|----------|----------|
| 1  | 120                 | -0.85                     | 19.3     | 2.53     |          |
| 2  | 240                 | 5.76                      | 15.79    | -1.94    |          |
| 3  | 300                 | 1.73                      | -25.21   | 28.37    |          |
| 4  | 420                 | 27.04                     | 3.38     | -7.24    |          |
| 5  | 540                 | -14.08                    | 29.26    | 9.57     |          |
| 6  | 630                 | 3.2                       | -18.04   | 21.1     |          |
| 7  | 750                 | 13.89                     | 20.01    | -17.51   |          |
| 8  | 840                 | 10.63                     | -23.46   | 5.75     |          |
| 9  | 960                 | 2.58                      | 0.59     | 4.22     |          |
| 10 | 1050                | 7.8                       | 5.94     | -13.56   |          |
|    | Average             | 5.77                      | 2.76     | 3.13     |          |

The reduction in erosion in every test is significant. The reduction in the erosion of H1 compared to L4 is 5.77%. Similarly, the reduction in the erosion of V2 compared to H1 is 2.76% and the reduction in the erosion of R3 compared to V2 is 3.13%.

Thus, after our experiment our test hypothesis is modified to a result as, Under the same operating conditions, amount of wear in the welded blades will be significant as follows:

Left inclined > Longitudinal > Transverse > Right inclined.

4.4 Rate of erosion

The rate of erosion can be defined as the amount of erosion per unit time of operation. The rate of erosion can be calculated using eq. (3).

\[
\text{Rate of erosion} = \frac{(w_i - w_j)}{(w_i \times \Delta t)} \times 1000 \quad [\text{mg/gm per min}] \tag{3}
\]

| SN | Test Duration (min) | Rate of erosion (mg/gm per min) | H1 | V2 | R3 | L4 |
|----|---------------------|---------------------------------|----|----|----|----|
| 1  | 120                 | 0.0031                          | 0.003 | 0.0033 | 0.0007 | 0.0008 |
| 2  | 240                 | 0.0039                          | 0.0033 | 0.0019 | 0.0028 | 0.0038 |
| 3  | 300                 | 0.0007                          | 0.0009 | 0.0018 | 0.0014 | 0.0008 |
| 4  | 420                 | 0.0019                          | 0.0018 | 0.0028 | 0.0017 | 0.0028 |
| 5  | 540                 | 0.0043                          | 0.0031 | 0.0014 | 0.0015 | 0.0008 |
| 6  | 630                 | 0.0015                          | 0.0018 | 0.0024 | 0.0028 | 0.0034 |
| 7  | 750                 | 0.003                           | 0.0018 | 0.0028 | 0.0034 | 0.0028 |
| 8  | 840                 | 0.0018                          | 0.0022 | 0.0021 | 0.0002 | 0.0036 |
| 9  | 960                 | 0.0035                          | 0.0035 | 0.0017 | 0.0017 | 0.0036 |
| 10 | 1050                | 0.0016                          | 0.0015 | 0.0023 | 0.0028 |
|    | Average             | 0.0026                          | 0.0024 | 0.0023 | 0.0028 |
Table 5 shows the rate of erosion in all four specimens for each test. It can be observed that the rate of erosion in specimen R3 is less than that all other specimens in all of the test runs. The average rate of erosion in specimen R3 is significantly lesser than other specimens which further justifies that the right inclined welding pattern is less affected by erodent than the rest. It can also be observed that the overall trend of the erosion rate for all test specimens is increasing with the total duration of the test run. This also implies that the rate of erosion is going to increase with increase in the time of exposure to erosion.

5. Uncertainty and Error

The sources of uncertainties and errors of the erosion rate for all the test specimens are identified and calculated. According to ISO GUIDE 5168-2005 uncertainties are classified as Type A and Type B.

**Type A:**
It is the evaluation of a component of measurement uncertainty by a statistical analysis of measured quantity values obtained under defined measurement conditions such as standard deviation. Type A evaluations in uncertainty estimates using statistics usually from repeated readings.

**Type B:**
Type B evaluations are uncertainty estimates from any other information. This could be information from past experience of the measurements, from calibration certificates, manufacturer’s specifications, from calculations, from published information, and from common sense.

**4.1 Calculation (for test specimen R3):**
Uncertainty and error is calculated for the test specimen with least sediment erosion i.e. R3

*Type A uncertainty from experimentation.*

Average (\(\mu\)) = \(\frac{1}{n} \sum_{i=1}^{n} x\) = 0.0023

Confidence interval = 95 %

Standard Deviation (\(\sigma\)) = \(\sqrt{\frac{1}{n-1} \sum (X-\mu)^2}\) = 0.0009

Standard error of mean (\(\delta\)) = \(\frac{\sigma}{\sqrt{n}}\) = 0.0003

Random uncertainty of mean (\(u_a\)) = \(\frac{\delta}{\mu} \times 100 = \pm 13.04\%\)

*Type B uncertainty of Electric weighing machine.*

Linearity of weighing machine for each observation = \(\pm 0.0003\) gm

Type B uncertainty (\(u_b\)) = \(\pm 0.01\%\)

Combined uncertainties (\(u_c\)) = \(\sqrt{u_a^2 + u_b^2}\) = 13.05 %

6. Conclusions

Comparative study showed that the test specimen with right inclined welding pattern is better than other test specimens at handling sediment erosion. The extent of wear was found to be significantly less in the right inclined welding pattern taking material loss as the basis for comparison. After an operation time of 1050 minutes, the average rate of erosion in the test specimens R3, V2, H1 and L4 are 0.0022 mg/gm per min, 0.0023 mg/gm per min, 0.0026 mg/gm per min and 0.0027 mg/gm per min respectively. The results also show that for prolonged operation, the amount of erosion in the welding repaired Francis runner blade with right inclined welding pattern keeps increasing with lower rate than other welding pattern.
These observations were made with relatively higher uncertainty due to use of low precision equipment during the experiment. This study reveals that the welding pattern is very important while welding repair of the sediment eroded turbine parts. Hence, careful investigation of welding is utmost during repair to ensure the required strength of the repaired turbine parts.

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Nomenclature

| symbol | Description                                      | Unit   |
|--------|-------------------------------------------------|--------|
| e_A    | Erosion in test specimen A                      | mg/gm  |
| e_B    | Erosion in test specimen B                      | mg/gm  |
| e_i    | Cumulative erosion after test i                 | mg/gm  |
| W_o    | Weight of test specimen at the beginning of the experiment | gm      |
| W_i    | Weight of test specimen before test             | gm      |
| W_j    | Weight of test specimen after test              | gm      |
| Δt     | Duration of test                                | min     |