KEEPING IT TOGETHER - HYDRO GENERATOR LEG TRANSPLANT

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Abstract

Unit 5 at Ohau A power station has been closely monitored since 2002 following the identification of a defect in a construction weld of one rotor spider arm. In 2003 it was determined that the defect, initially identified in 1996, was beginning to grow and there was evidence of further defects developing. By the end of 2005, after substantial analysis, risk studies and the discovery of a further 18 defects, the unit was removed from service to effect a rotor arm replacement.

The following paper covers the four years of condition monitoring, defect analysis and risk studies that were carried out on the rotor spider prior to the complex physical works of replacing a rotor spider arm. The paper will also cover, in brief, the physical works carried out during the rotor arm replacement. This work highlights the benefits of routine engineering assessments and the use of non destructive testing methods in assessing critical defects.

1. Meridian Energy Assets

Meridian Energy is the largest state owned electricity generator in New Zealand. It owns and operates nine hydro stations in the South Island, New Zealand's largest wind farm in the North Island, and a wind turbine in Wellington.

The hydro assets are broken up in to the Waitaki Valley and Manapouri. The Waitaki scheme consists of eight power stations containing 32 generating units ranging in size from 15 MW to 90 MW. The Manapouri scheme consists of one station and seven 135 MVA units.

Hydro units generate electricity by harnessing the gravitational potential energy available from the water. The water flows down to the turbine via the penstock and into the scroll case. The turbine runner is located in the centre of the scroll case in a circle of guide vanes and wicket gates that direct and control flow to the runner to vary the output power.

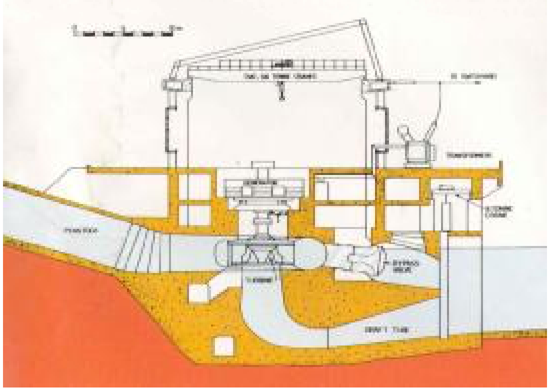


Figure 1 *Cross section of Ohau A Power House*

The runner is connected to the generator rotor via the main shaft rotating a set of electromagnets within the stator to generate electricity.

1.1. Ohau A and Unit 5

The Ohau A Power station houses four 66MW units that were designed and constructed in Yugoslavia and Czechoslovakia. They were commissioned between 1979 and 1980.

The power station is located in the central South Island high country approximately 6 km out of Twizel at the end of the Pukaki Canal. The 12km long Pukaki Canal and the 8.3km long Ohau Canal carry water form Lake Pukaki and Lake Ohau respectively to the station. The 60.3m head difference between the canal and Lake Ruataniwha provides the station with sufficient energy to

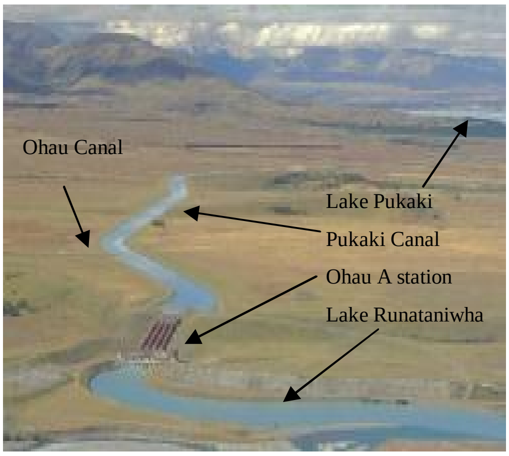


Photo 1 *Ohau A Power Station location*

produce 1150 GWh per year.

2. Ohau A Rotor Construction

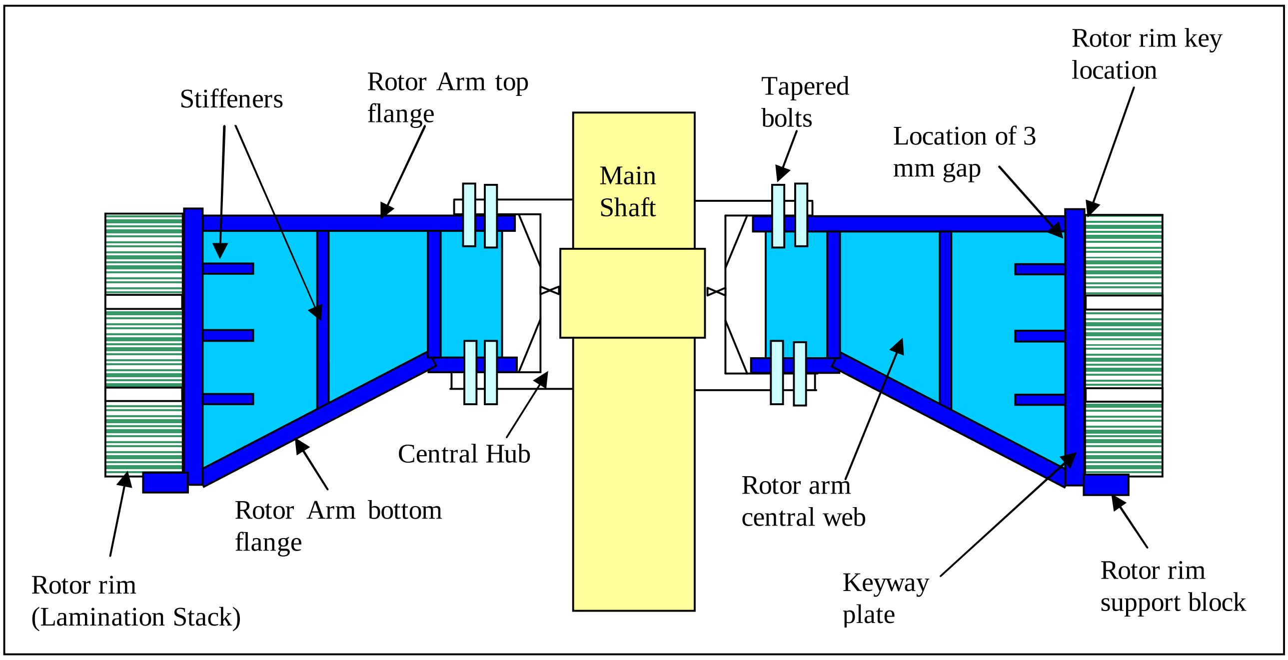


Figure 2 *Detail of rotor construction and part names*

The rotor construction consists of a central hub that is keyed on to the main generator shaft with nine independent rotor arms that are attached to the hub by 16 fitted bolts to form the rotor spider. The rotor rim is made up of hundreds of laminations that are stacked around the outside of the nine rotor arms (see Figure 2) and bolted together to form a solid ring.

The rotor arms are constructed similar to I beams. They consist of a top flange, a central web, a bottom angled flange and several vertical and horizontal stiffeners.

The rotor is constructed similar to a wheel. The nine rotor arms are evenly spaced around the rotor hub and act like spokes of a wheel (known as the rotor spider). The rotor rim acts like a solid steel rim. The rim is attached to the rotor spider via nine sets of taper keys that apply a 1.1mm interference fit per arm. This interference fit is achieved by heating the rim up and driving the keys down a known distance.

This type of rotor rim construction will effectively place the whole rotor spider into compression during normal operation. As the unit spins the compression force is reduced due to the increase in centrifugal force applied to the rim. The normal design criterion for a heat shrunk rim is that the compression force is reduced to zero when the unit reaches runaway speed (220% of nominal speed at Ohau A).

2.1. Defect History

In 2002 a small crack was identified in one of the spider arms on Unit 5. Initially of little concern, the defect was again inspected a year later when it was reported to have ‘opened up’.

During the first Non Destructive Testing (NDT) of the defect, known as defect 1, three additional cracks were found, defects 2, 3 and 4. The three new defects were all discovered in the same construction weld between the central web and keyway plate.

The discovery of these additional defects caused some alarm once it was identified that there was a 3mm gap between the central web and the keyway plate. The presence of this gap allowed the construction welds to be loaded in pure shear by the heavy compression forces of the heat shrunk rim.

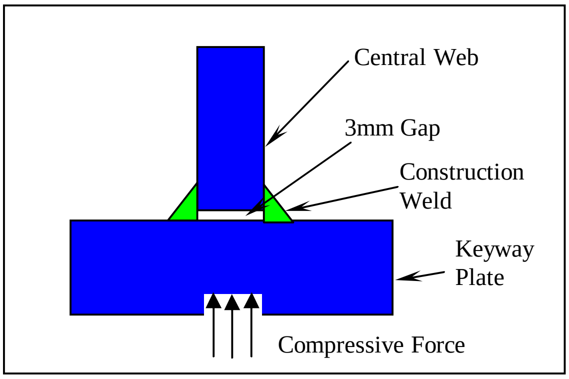


Figure 3 *Detail of construction weld and 3mm gap*

The first reaction was to carry out a weld repair on the cracks, but the construction of the rotor caused the engineers to stop and think.

Photo 2 *MPI of defective rotor arm*

Over the next three years the defects were monitored and a detailed risk assessment of the unit was carried out.

3. Defect Condition Monitoring

Southern Quality Assurance (SQA) was engaged to help monitor the growth rate of the defects both on the surface and where possible sub surface with the use of ultrasonic testing.

Southern Quality Assurance (SQA) is an NDT company located in Christchurch New Zealand. SQA has certifications in NDT methods (Ultrasonic Testing (UT), Radio Graphic (RT), Magnetic Particle Inspection (MPI) and Particle Testing (PT)) and welding inspection. It is an IANZ Accredited Laboratory, accredited to ISO 17025.

The defects were visually inspected every three months, with NDT applied every six months to track defect growth rate. The NDT consisted of MPI and UT inspections.

The MPI was used to confirm the surface length of all defects for trending purposes. It also allowed for the smaller, <5mm, defects to be identified which indicated a larger defect subsurface.

The UT was predominately used to determine the depth of the defects and the fabricated design of the arm. It was through UT that the critical 3mm gap was identified that placed the construction weld into pure shear.

The results from the defect monitoring were trended against operational hours and used to determine the rate of crack growth and thus the time to failure.

4. Defect Assessment

MPT Solutions was engaged to answer several important questions surrounding these defects.

MPT Solutions is owned by Quest Reliability LLC, a subsidiary of Quest Integrated Inc. They deliver state-of-the-art reliability engineering solutions to key industries world-wide with a strong focus on Australasia and South East Asia.

The questions asked were:

- Is it a design issue or a material issue that is causing the cracks to propagate?

- Is it a changing load or the general loading arrangement that is the cause of the crack propagation?
- What happens if the welds were to fail completely?
- How long can the unit run under standard operating conditions before the welds are deemed to fail?
- How can we repair these defects?
- Do we have to repair these defects?

To answer these questions MPT carried out 3 sets of analysis.

4.1. Material Assessment

The first set of analysis was a material and crack assessment. It involved a physical inspection of the defects, hardness tests and several 'replica[1]' samples of the welding material, plate material and the heat affected zones (HAZ).

The results of this analysis indicated that the cause of the defects was pointing towards the welding preparation and final capping weld, a single pass 20mm wide fillet weld. It was also believed that there was very little post weld heat treatment thus causing large residual stresses within the HAZ.

The driving force for crack propagation was unknown at this stage but was believed to be due to a combination of rotational speed and megawatt loading.

Photo 3 *The heat affected zone next to defect3 (Photo extracted from MPT report 11541.01)*

It was also noted in MPT's report that careful consideration should be given to any repair methodology of the defects in the vertical weld between the keyway plate and the central web.

The results of the analysis indicated that the material was a low carbon steel (<0.18% carbon) with no 'normal' pearlitic structures, thus it is impossible to determine if the arm had been heat treated. There was no evidence of hardening having occurred in the HAZ due to abnormal cooling rates. The overall material was deemed satisfactory.

4.2. Stress Analysis of the Rotor Arm

Out of the above analysis several questions required answering:

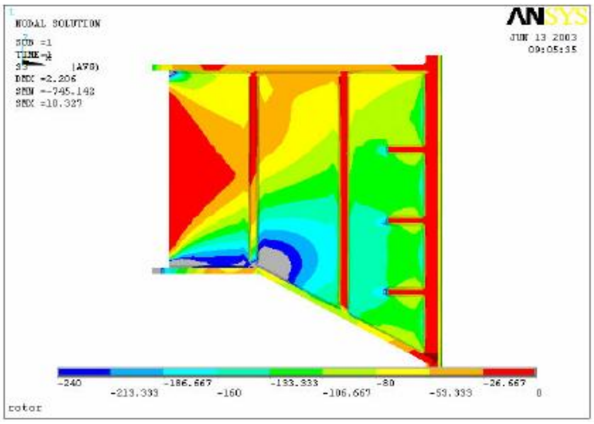
- How is the arm, and effectively the defects, loaded?
- What are the forces in the areas around the defects?
- Is the design of the rotor arm adequate for the given loads?

To answer these questions a 3D Finite Element Analysis (FEA) stress analysis was undertaken on the rotor arm.

The results of the FEA indicated that the whole arm was in compression due to the large 'heat shrink' force from the rotor rim. The loading effect from the generator's torque had very little effect on the overall loading of the arm.

The main oscillating loading effect was from the change in unit speed. At 0% speed the compression loading from the rotor rim was at its maximum, as the speed increased to 100% and into overspeed (taken as 130% speed) the compression force from the rotor rim reduces (see table 1 for values).

Case	***Defect***		
	1	***2***	***3***
0. Fabricated stresses (MPa)	0.0	0.0	0.0
1. No rotation (MPa)	-248.0	-224.3	-210.8
3. Operational speed no load (MPa)	-171.2	-165.5	-154.2
4. Operational speed and power generation at 65MW (MPa)	-160.5	-151.7	-153.1
5. Over speed (130%) (MPa)	-122.0	-128.7	-118.6
Residual stresses (MPa)	*265.0*	*265.0*	*265.0*



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[1] A replica is an imprint of the micro structure of a material onto a small microscope film

Table 1. *Summary of results give in terms of third principal stress (unit are in N/mm^2)*[1]

The basic FEA results indicated that the arm design was good and should not allow the arm to fail in fatigue as the predominant loading was compression. However, fatigue cracking requires the crack to be in tension if it is to propagate.

Figure 4 *FEA stress distribution of 3rd principal stresses with no rotation*[2]

In the case of the rotor arm the only way that the defects can be in tension is if there are 'tensile residual stresses' due to a lack of post weld heat treatment (PWHT). The residual stresses are normally taken as the material yield stress (i.e. 265 MPa). Thus if residual stresses are present due to a lack of PWHT then there will be an oscillating tension force in the areas of all defects. In the case of defect 1 the oscillating force is between 17 and 143 MPa in tension.

4.3. Defect Assessment and Residual Life Assessment

The next big questions that required answering were:

- What happens if the welds were to fail?
- How long can the unit run under standard operating conditions before the welds are deemed to fail?

4.3.1. Failure Simulation

The further FEA analysis involved removing the vertical keyway welds completely to simulate complete failure of the welds. The first step involved removing the TE weld and observing the distortion in the key way plate. The results indicated that a distortion of up to 0.07 mm in the keyway slot could be expected. The second step involved removing both vertical welds from the keyway place. The results were not so favourable with a maximum distortion of up to 0.42 mm. Almost half of the heat shrink (designed to be 1.1mm at 0% speed and 0.9 mm at 100% speed). The removal of the welds allowed the rotor arm to distort as shown (in distorted form) fig 5. The distortion is predominantly due to the 3mm gap.

The distortion of the keyway plate places additional loading on the 6 stiffeners located between the keyway plate and the central web. Stress calculations were carried out on the stiffeners and the surrounding plate material. The results indicate that with both welds removed a maximum shear stress of 129.3 MPa can be expected. This shear stress is just below the maximum permissible shear stress of 132 MPa.

The conclusion from the above results indicates that the complete weld down each side will have to be deemed to have failed before the keyway will experience any significant movement. If a defect is present on both sides in a localized region the distortion is not expected to be as severe. However areas around the top and bottom of the keyway plate are susceptible to excessive movement if the welds have been deemed to fail on both sides.

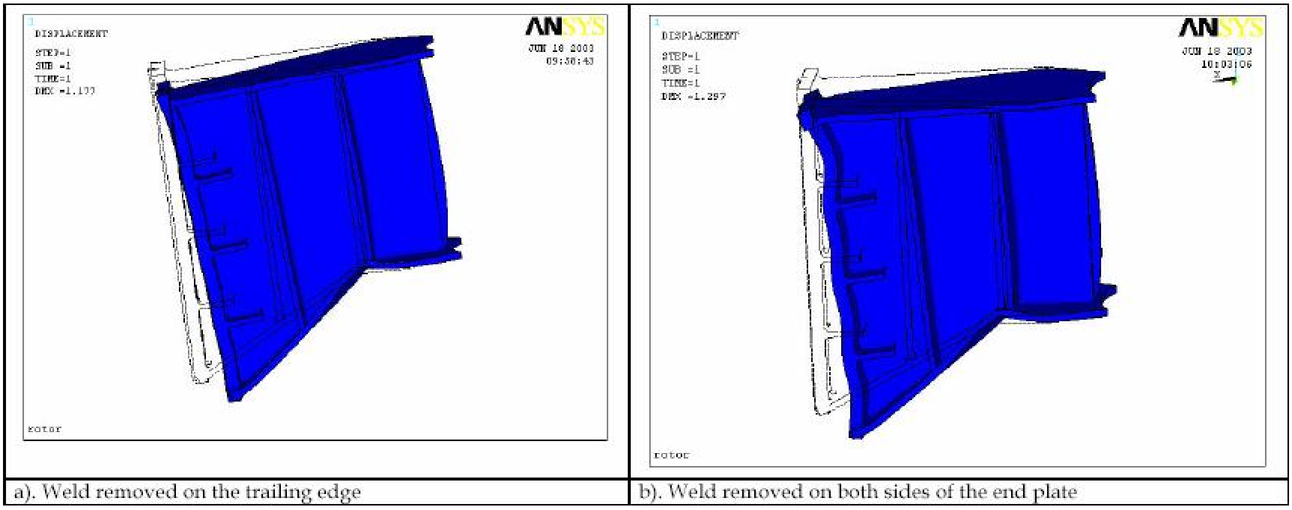
4.3.2. Residual Life Assessment

To answer the time to failure question a defect assessment was carried out utilizing the NDT crack growth data and the FEA analysis.

The defect assessment estimated the maximum size that the defects can grow to before they are deemed to be 'critical' and an estimation of the operating time of the unit before the cracks become critical.

Based on the measured defect growth rate and operational loads the following critical crack lengths were calculated (see table 2 below).

Defect	**1**	**2**	**3**
Recorded defect height (mm)	14	10	10



a). Weld removed on the trailing edge

b). Weld removed on both sides of the end plate

Fig 5. *Showing the displaced shape of the rotor arm during over-speed conditions, for two different*

Recorded defect length (mm)	220	133	242
Max tolerable flaw depth, (mm)	***24***	***26***	***21***
Max tolerable flaw length, (mm)	***290***	***281***	***293***

Table 2 M*aximum tolerable flaw sizes based on NDT data from 13 May 2003*

The critical crack dimensions were based on an assumption of a constant depth/length ratio.

The calculations for the 'residual life' of the rotor arm were based on historic crack growth rates and their 'calculated equivalent Stress range'. These stresses were then feed into the 'residual life' equation: $da/dN = A\,\Delta K^m$ where;

da/dN = fatigue crack growth rate

A = material growth constant

ΔK = stress intensity factor range in the cycle

m = exponent in growth law (material constant)

The resulting crack residual life (calculated in cycles) was then converted into running hours.

Defect	**1**	**2**	**3**
Hours of operation to reach maximum tolerable flaw size based on defect size from 13 May	410	1580	1890

Table 3 *Number of operating hours to grow from the defect size measured on 13 May 2003 to those given in Table 2*[1]

Based on the above analysis and regular NDT inspections an interim weld repair of defect 1 was carried out in September 2003 [1]. The repair was carried out using the bead tempered weld repair to remove / reduce the likelihood of additional residual stresses building up around the repaired defect.

The fracture surface was analysis and the root cause of the cracking was put down to tearing during the construction process due to heavy distortions and construction methodology. The measured crack growth rate was due to operational cyclic loads growing the defect in fatigue.

5. Limitations of the NDT,

During the repair of defect 1 in September 2003 it was noted that the defect profile did not fit with that determined by the UT. The defect was longer and deeper than initially expected. Difficulties experienced in defect sizing were:

- The presence of significant original welding defects in the root of the fillet welds, which had propagated during the service life of the rotor
- The orientation of the defect
- The presence of both root and toe defects in the same area.

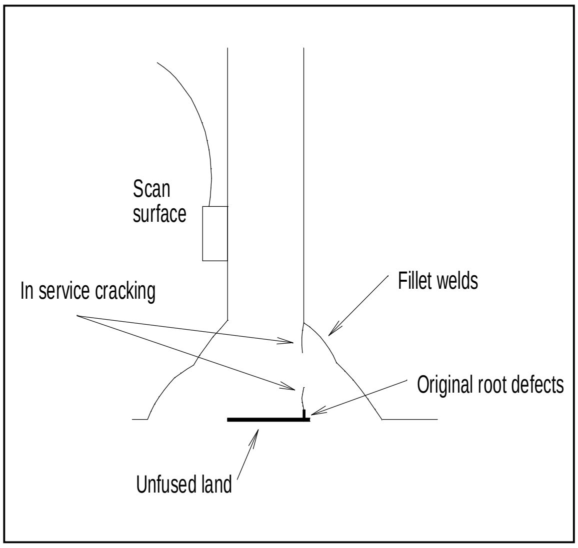


Fig 6 *Detail of defect location and orientation*

Tip diffraction methods for defect tip sizing work well when the defect lies in a plane perpendicular to the scan surface. The application of tip diffraction to size the defects in the rotor welds was attempted, but only limited success achieved.

These limitations of the UT method used for detecting and sizing of the defects in the fillet welds, under estimated the defect size. This may have had serious consequences resulting in premature failure of the rotor.

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[1] The assessment used as-welded conditions and taking account of compressive stresses. Table extracted from MPT report 11541.03.

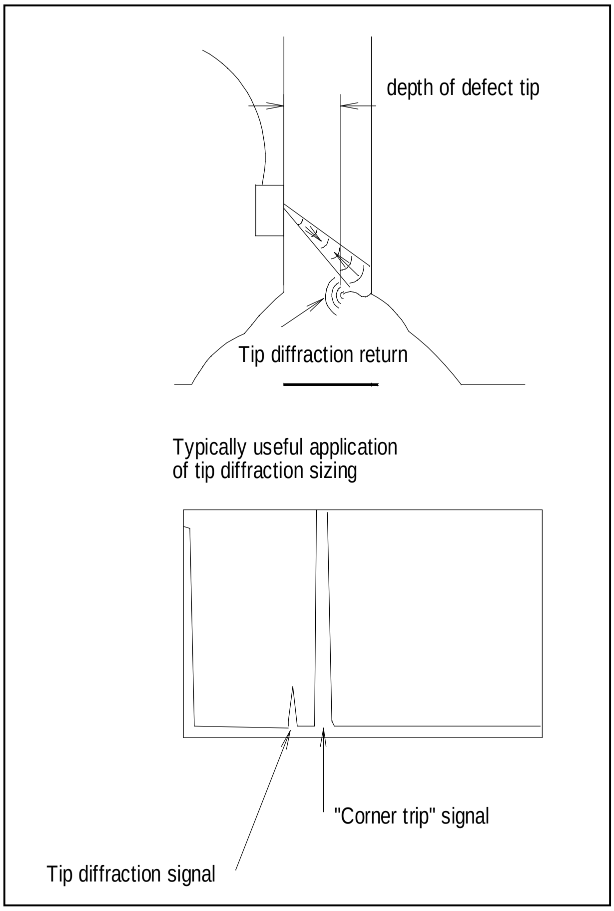

Figure 7 *Tip diffraction signal*

6. Arm replacement

After the repair of defect 1 the continued growth rate of defect 3 was still of concern. It was predicted that the crack would reach a critical length by November 2005. This prediction was based on the applied loads, measured crack growth rate and the current operating conditions of the unit.

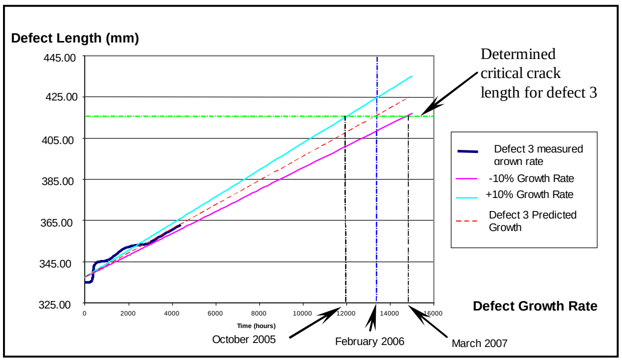

Figure 8 *Trending of the defect 3 growth rate to critical crack length*

The call was made to carry out a full arm replacement in October 2005.

6.1. Manufacture and Quality Assurance of the new arm

The new arm was manufactured in a workshop in Christchurch. Like the existing arm, it was a fabricated construction with the welding requirements based on the bead tempered weld procedure used in the initial repair of defect 1 [1].

As part of the acceptance process for the arm, a detailed NDT inspection was carried out. The initial result indicted that the weld profiles did not comply with the required profiles as specified in AS/NZS 1554 part 5 and thus it was rejected even though there were no detectable defects.

All the welds were dressed back to remove stress concentrations, weld undercut and other defects that may lead to fatigue in service.

Photo 3 *The new arm under construction.*

6.2. Physical Site Works

The physical site works were carried out by Transfield Services. The simplicity of the rotor rim removal and reassembly was the key to the successful replacement of the arm.

The unusual requirement of removing the rotor rim whole was tackled by the use of induction heating of the rim [3]. Once the rim was heated up to 70ºC, creating a 1.1mm expansion per arm, the rim keys were easily extracted and the rim removed.

With the rim removed it allowed full access to the rotor arms for additional inspection and replacement of the defective one.

6.3. Further NDT Inspections and Repairs

After the original arm was removed the eight remaining arms were tested by SQA (predominantly MPI). A number of significant defects were identified in three additional arms.

Photo 4 *NDT and weld repairs of the rotor*

With the use of UT it was identified that the critical gap behind the weld see figure 3 was not present[1] and the number of defects were manageable, so it was decided to carry out a weld repair of these defects.

To reduce the likelihood of residual stresses and potential fatigue issues, the bead tempered weld repair was used (as per the repair of the original defect 1 [1], [8]).

7. Conclusions

Meridian considers the repair of Ohau A Unit 5 as “just in time” maintenance based on the measurable condition of the defects.

The ability to carry out insitu subsurface NDT in the form of UT has enabled Meridian to identify the critical 3mm gap that placed the construction welds in full shear. The actual defect growth rate enabled MPT to pin point the time to failure of the defects enabling Meridian to affect a repair of the unit prior to the defects reaching critical length and thus unit failure.

Development of UT techniques has focused on through-wall defect size determination. The Ohau A project has highlighted the need for development of other techniques for on fillet weld defect detection.

8. References

[1] Wilson J, Karstensen A and Firth D, “Fitness for purpose of the Ohau A G5 rotor arm with known propagating defects”, *11th Hydro Power and Engineering Exchange*, Taupo 2004.

[2] Firth D and Wilson J, “Repair Welding at Ohau A ”, *11th Hydro Power and Engineering Exchange*, Taupo, 2004.

[3] Wilson J, Marsh T, Jay S and DeBono J. “Despite the Myth, Engineers Can Put Things Back Together After Taking Them Apart. Repair of the Rotor Arm at Ohau A Power Station”, *Electrical Engineering Association*, Auckland, 2006.

9. Acknowledgements

The writers of this paper would like to acknowledge the hard work and time that the following people have put into this project to ensure a successful outcome.

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- MPT for the long hours behind the computer and time on site away from home. Special thanks to David Firth and Annette Karstensen.
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[1] Thus not placing the weld in shear and allowing movement of the keyway plate if the weld was removed.