THE USE OF FRACTURE MECHANICS FOR ASSESSING RELIABILITY OF WELD REPAIRED STEAM TURBINE ROTORS

A.A. TIPTON
Steam Turbine, Motor & Generator Division
Dresser-Rand Company, Wellsville, New York, USA

ABSTRACT

This paper presents a novel approach for assessing the reliability of weld repaired steam turbine rotors and the type of data required to support the analytical method. A conservative assessment method is described based on "fitness for purpose" concepts ,which addresses the shortcomings of "good workmanship" practices. The methodology incorporates the specific detectability limit of nondestructive testing, threshold and near-threshold fatigue data of the various weld zones and analytical techniques of linear elastic fracture mechanics to estimate the reliability of any turbine rotor prior to performing the weld repair.

KEYWORDS

Reliability, weldments, fatigue, fitness-for-service, steam turbines, rotors, repair

INTRODUCTION

Several successfully completed rotor weld repairs in the United States and elsewhere has shown that weld repair is a viable alternative to early retirement of damaged rotors. These weld repairs were completed using what is commonly referred to as "good workmanship" practices, i.e. close attention to weld technique and joint design, matching of filler metal and base metal mechanical properties and extensive nondestructive inspection of the completed repair weldment. However, the reliability of any of these weld repairs has been demonstrated only through actual operation of the salvaged rotor. The ability for any of these weld repaired rotors to operate safely during continued operation is not known a priori nor can the success of any one weld repair be used as a basis for the reliability of another rotor unless weldment characteristics and operating conditions are identical. In all fairness it must be pointed out that there have been no reported failures associated with any rotor weld repaired using the "good workmanship" methodology; I suspect that this is a reflection upon the forgiveness built into original designs. In all but a few cases the fatigue resistance of the repair weldments has been neglected even though all rotors are subject to both high cycle and low cycle fatigue loading. Where the fatigue characteristics have been investigated the properties have been reported using classical S/N type curves generated on weldment specimens which quite often do not represent the actual condition of the repair weldments; this subject will be discussed further in a subsequent section of the paper. The use of such data could lead one to underestimate the resistance of the actual repair weldment resulting in unnecessary and expensive designing of the weldment while in other cases the data may overestimate the properties of the repair weldment resulting in failure during operation.

This paper will present an alternative to the "good workmanship" practices utilizing linear elastic fracture mechanics as the basic analytical tool to quantitatively assess the reliability of any rotor weld repair embodying the basic concepts of "fitness for purpose" philosophy as defined by Wells (1981):

> "Fitness for purpose is deemed to be that which is consciously chosen to be the right level of material and fabrication quality for each application having regards to the risks and consequences of failure".

The method outlined in this paper provides for a realistic assessment of repair weldment reliability for any weldment geometry, base metal/filler metal combination and turbine operating conditions. With adequate up front development the analysis may be performed prior to actually welding the rotor allowing the user to plan for outages and eventual replacement components should the rotor repair be identified to be life limited. The results of the weld repair development efforts including all mechanical testing has been previously presented by Tipton (1991).

LIFE ASSESSMENT METHODOLOGY

When a decision is made to utilize linear elastic fracture mechanics as an assessment technique one must generate both fatigue crack growth data for various weldment zones and evaluate the detectability limit(s) associated with the type of non-destructive inspection to be performed. The attainment of such information is not straightforward and one will be required to make several engineering judgements along the way to insure that the data is sufficient without being excessive.

Fatigue Data. As previously mentioned where the fatigue properties of repair weldments has been generated it has been based on classical S/N type data obtained from smooth configured weldment specimens. It is well known that the fatigue behavior of metals is a function of monotonic tensile properties and defect severity/frequency. Furthermore Lawerence et al (1987) has shown that weldment fatigue behavior is also a function of weldment geometry and loading direction. Therefore it is not surprising that S/N type fatigue data presented for weld specimens generally exhibit an order of magnitude scatter. To go one step further one can argue that if it is assumed that a linear discontinuity may exist in a weldment, the specific area of the weldment being unknown and therefore the strength level of the area unknown, the use of such S/N fatigue data from smooth configured specimens is basically feckless.

Fracture mechanics analytically accounts for the defect severity/frequency, weldment geometry and loading condition however, the materials engineer must decide what zones of the weldment should be tested and how to simulate each condition to be tested. Where overlay type weldment repairs are envisioned it is necessary to generate threshold and near-threshold crack growth data for the base metal, rehardened heat affected zone and filler metal. It is also necessary to generate crack growth curves in the Paris region for the base metal, in the case of overlay type weld repairs and also for the filler metal where complete wheel buildups and through shaft repairs are anticipated. Initially we intend to use only overlay type welds and therefore Paris region crack growth data was not necessary for the filler metal and the heat affected zones for it was clear that the majority of any crack growth would occur in the rotor base metal. Crack growth data and fracture toughness for the base metals of interest had been previously investigated by Poon et al (1983). Threshold and near-threshold crack growth data was generated for the filler metal by machining specimens from a pad of weld filler metal build up sufficiently thick to preclude any dilution effects. Similar data was obtained for the rehardened area of the heat affected zone by using specimens of base metal composition and performing a heat treatment consisting of austenitizing, quenching and tempered at 552°C ; the tempering temperature is equal to the stress relieving temperature of the actual weldments. All testing was performed at room temperature in compliance with ASTM E647.88a using three point bend specimens and the decreasing ΔK method. In all cases data was generated at R ratios of 0.1, 0.5 and 0.8. Fracture toughness of the heat affected zone and filler metal was not determined by test since it was expected that the rotors would be able to tolerate a crack much deeper than the thickness of the weldment before attaining critical size.

Detectability Limits of Ultrasonic Inspection. It is presumed that all weldments are inherently prone to the generation of flaws, albeit severity is a function of close attention to detail, and that any nondestructive inspection method has an associated detectability. The detectability limit is defined as the probability of given method to detect flaws above a certain size with a arbitrarily defined confidence level. Linear discontinuities, cracks, are the defects of utmost concern for rotor weld repair and the analytical technique requires the crack depth detectability limit to be determined. For the geometry involved in our weld repairs it was decided to use both longitudinal and shear wave inspection methods to evaluate linear discontinuities. To evaluate the detectability limit of the UT technique plates of alloy steel similar to the rotor alloy composition were notched and subjected to high cycle fatigue loading producing cracks of various depths in each plate. The plates were then machined to remove the notches and a weld overlay applied over the cracks. The plates were subsequently machined flat containing embedded cracks with depths ranging from 0.16 cm to 0.50 cm. The plates were then subjected to repeated inspection by the inspectors at the service center facility as well as outside consulting firms. Upon completion of the inspections the plates were fractured open to accurately measure the depths of the embedded cracks. It was determined that the inspectors using equipment prescribed would confidently detect cracks above 0.16 cm in depth. Calibration during actual inspection is performed on circular shafts, of diameter similar to the rotor to be inspected, with 0.16 cm deep notches machined into the outer surface and the hollow inner surface which contains stepped counterbored inner diameters. Calibration in this manner accounts for attenuation of the sound through the metal and provides the inspector with a DAT type curve.

Analytical Reliability Method. The life assessment is composed of a two tier system. First a series of calculations is performed to determine if the initial flaw will grow during continued operation. The initial flaw size is assumed to be equal to the detectability limit obtained from the test plates discussed previously, the threshold stress intensity factor range value is obtained from the test data for the material of interest and the loading conditions are based on customer supplied information regarding the future operating conditions. The orientation of the initial flaw is located to insure conservatism during the analysis. All variables are assigned statistical distributions based upon previous observations, trends reported in the literature and good engineering judgement and the calculations described below are performed in a probabilistic manner using first and second order reliability methods described by Singh (1991).The deterministic portion of the calculations are performed using standard forms of equations from linear elastic fracture mechanics such as:

$$\Delta K = Y \Delta\sigma \sqrt{a} \qquad (1)$$

The constraint condition to determine if the initial flaw will grow is set up as follows:

$$\Delta K_{th} \geq \Delta K_{cal} \qquad (2)$$

If the analysis indicates that the initial flaw will not grow with a high degree of confidence then no further analysis is necessary. If however the reliability is such that the likelihood for growth occurring is unacceptable than a more detailed analysis is performed. In this second tier of the assessment it becomes necessary to calculate the number of cycles which will elapse before the flaw reaches a critical size after which unstable crack extension would be anticipated. To complete this tier of the analysis the crack growth is modeled using crack growth data from the weld metal, heat affected zone and base metal as required. The crack propagation is summed up from incremental steps in the near-threshold and Paris regions as follows:

$$N_f = \sum_{a_i}^{a_j} da + \int_{a_j}^{a_f} \frac{da}{CY^n \Delta\sigma^n a^{n/2}} \qquad (3)$$

If Y varies with the crack length the cyclic life is estimated using standard numerical integration procedures. It is implicit that when a second tier analysis is required the repaired rotor will have a finite life expectancy after which it will have to be retired.

Since weld repair is not confined to the areas of the rotor experiencing only ambient temperatures it was necessary to establish guidelines for estimating the crack growth behavior at elevated temperatures from room temperature data. This was accomplished to a first approximation by normalizing the crack growth data with respect to the degradation observed in Youngs Modulus as described by Shahinan and Sadananda (1982).

REFERENCES

Jutla, T., " Probabilistic Fracture Mechanics and Reliability Analysis- An Overview", Proceedings of the Sixth Annual North American Welding Research Conference, Edison Welding Institute, Columbus, Ohio, 1990.

Poon, C., Vitale, D., Singh, M. and Hoeppner, D., Int. J. Fatigue, Vol. 5, No. 2, 1983, pp. 87-93.

Shahinan, P. and Sadananda, K., " High Temperature Near-Threshold Fatigue Behavior", Proceedings of Conference on "Fatigue Thresholds, Fundamentals and Engineering Applications". Edited by J. Backlund, A.F. Blom and C.J.Beevers, Chameleon Press Ltd., London, 1982.

Singh, M., "Reliability Evaluation of a Weld Repaired Steam Turbine Rotor Using Probabilistic Fracture Mechanics", Proceedings of the International Joint Power Generation Conference, San Diego, California, 1991.

Tipton, A., "Steam Turbine Rotor Weld Development Based Upon Fitness For Purpose Philosophy", Proceedings of the International Joint Power Generation Conference, San Diego, California, 1991.Wells, A., International Conference on Fitness for Purpose Validation of Welded Constructions, The Welding Institute, London, 1981.

Walker, W., Walsh, W. and Lawerence, F., "Laboratory Fatigue Testing of Selected Weld Steel Connections for Freight-Car Design", Report R-645 of the Association of American Railroads Technical Center, September 1987.