Failure Investigation of Large Wind Turbine Transmission Housings

by Peter C. Riccardella, George J. Licina, Darryl A. Rosario, Richard L. Bax

Abstract

When a significant percentage of wind turbine housings from a major U.S. manufacturer experienced failures in their first eighteen months of operation, Structural Integrity Associates was retained by an operator of the turbines to perform an independent assessment of the manufacturer's root cause analysis, and to provide recommendations for potential remedies. The failure investigation resulted in a thorough understanding of the cause of the problem, and ultimately, led to recommended operational restrictions and metallurgical treatments which permitted the wind field to continue operating at an acceptable, statistically established failure rate.

Introduction/Problem Description

The ductile cast iron transmission housings of the large, 410 KW wind turbines produced by a major U.S. manufacturer were failing at an alarmingly high rate after only short operating periods (one or two wind seasons). As illustrated in Figs. 1 and 2, the failures initiated as corner cracks at a gusseted transition section between the main turbine housing and a heavy base plate used to affix the turbine to the tower. Once initiated, the cracks propagated through the wall of the housing, ultimately leading to leakage of oil from the housing, and necessitating shutdown of the units. The failure investigation described in this paper was performed to identify both short term and long term measures which could be used by a wind field operator who had recently installed over fifty such turbines. At issue was the efficacy of remedies to the problem proposed by the manufacturer, and whether the operator should accept final turnover of the wind field.

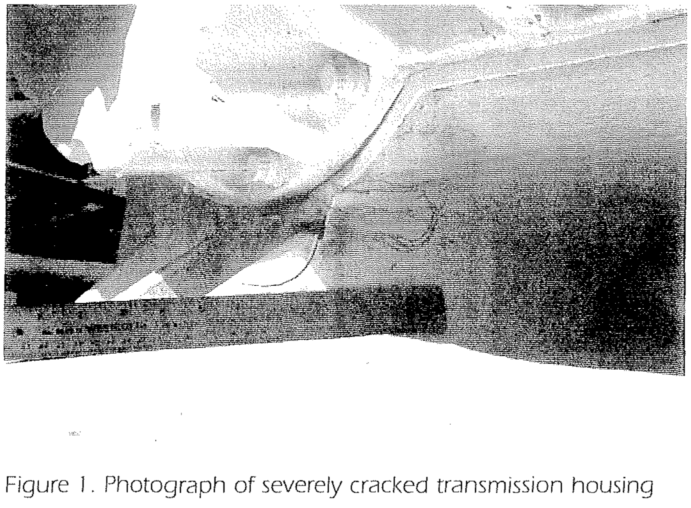

Figure 1. Photograph of severely cracked transmission housing

Failure Investigation Details

Structural Integrity Associates obtained material from the manufacturer, including specimens containing the more severe cracking, and material from unfailed locations for mechanical properties testing (Figs. 2 and 3). The manufacturer also provided housing design details, which were used to create analytical models (Fig. 4), but very little information was available on the magnitudes of anticipated loads on the housing under various operating conditions. With this as input, the failure investigation proceeded via the following major steps.

1. Metallurgical Analysis – The metallurgical failure analysis included optical metallography, plus optical and scanning electron fractography. The material was found to be "as-specified", without excessive surface or internal defects for a casting of this category. Selected locations on the fracture surface from the largest crack, numbered (1) through (4) in Figure 2, were examined in the SEM. The fracture surface showed definite beach marks (visible with the unaided eye and in the SEM) and striations. Using the SEM photographs, striation spacing was estimated for various sections of the fracture surface. The resulting striation count was then used to estimate the crack propagation rate.
2. Crack Growth Rate Testing – In addition to the field failures, fatigue crack growth specimens were machined (Fig. 3) from the same transmission housing, and tested in the laboratory under controlled loading conditions. The fracture surfaces from these specimens were also examined in the SEM in order to compare the fracture surface characteristics from housing material loaded under unknown conditions (field failures) to those from well-characterized loadings (fatigue crack growth specimens). The objective of this activity was to provide information on the probable time and number of cycles for crack growth and to estimate the stress range that must have existed in the field to produce the observed fatigue failures.
3. Finite Element Stress Analysis –The authors developed a finite element submodel of the local region of the trans

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mission housing in the vicinity of the gussets (Fig. 4). The sub-model included only those portions of the housing and adjacent components believed to be of significance to the cracking. A painstakingly detailed mesh was used in the vicinity of potential stress raisers, such as the fillet between the gusset and the housing body (i.e. the crack initiation site). The model was loaded using vertical tractions of 1000 lbs./in. along the top surface of the internal gusset and cover flange, as illustrated in Fig. 4. This loaded region is in the direct load path between the rear, main shaft bearing and the cracking region. Applying loads over this region is considered a reasonable approximation of the wind loading on the housing at the crack location. Since the absolute magnitude and direction of the wind loading were unknown at the time of modeling, an arbitrary value of 1000 lbs./in. upward was assumed as a unit load which could later be scaled up or down as appropriate. The resulting stress distribution is illustrated in Fig. 5.

4. Fracture Mechanics Crack Growth and Critical Flaw Size Analysis – As illustrated in Fig. 6, a quarter-elliptical crack was modeled at the highest stressed horizontal section in the finite element model in order to predict stress intensity factor versus crack size. The stress intensity range computed in this manner was used as input to a Paris Law crack growth model derived from the fatigue crack growth testing described above, Fig. 7. The computed stress intensity factor range was scaled to a value consistent with the observed crack growth rate / striation spacing in the field failures. This yielded a prediction of the actual load amplitude and number of cycles which must have occurred to produce the observed failures.
5. Field Strain Gage Measurements – To supplement the above analysis results and to obviate the need for scaling of load amplitudes, strain gages were installed on an operating wind turbine in the field, and strains were measured during periods of high wind loading. The results confirmed the analytical predictions, and provided additional input to the failure investigation, including cyclic frequency (3 cycles per revolution), mean stress and load spectrum of the excitation. It also demonstrated that the peak amplitude of the stress is correlated with the power level at which the wind turbine is operated. (Significant load differences were measured, at the same wind velocity, for the turbine operating at 410 KW versus 360 KW.)
6. Statistical Damage Fraction Analysis – The above results were used as input to a statistical damage fraction analysis of the wind turbine housings in various metallurgical conditions, at the two operating power levels tested (360 KW versus 410 KW). The analysis utilized fatigue crack initiation data for the as-cast material condition, as well as for two forms of metallurgical improvement which could be applied to the housings in the field

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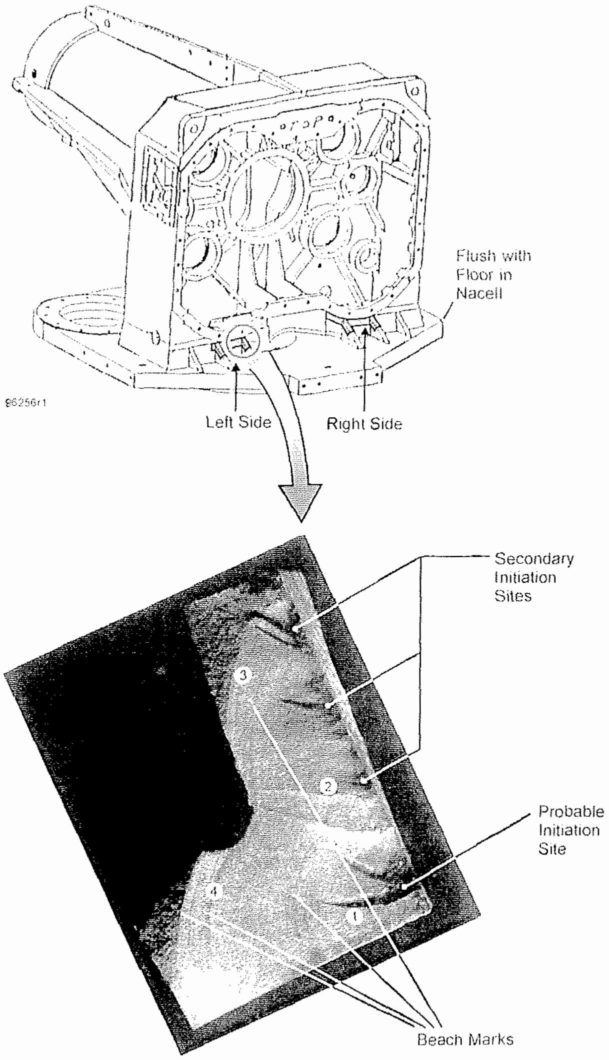

Figure 2. Schematic of transmission housing showing location and macrograph of most severe cracking

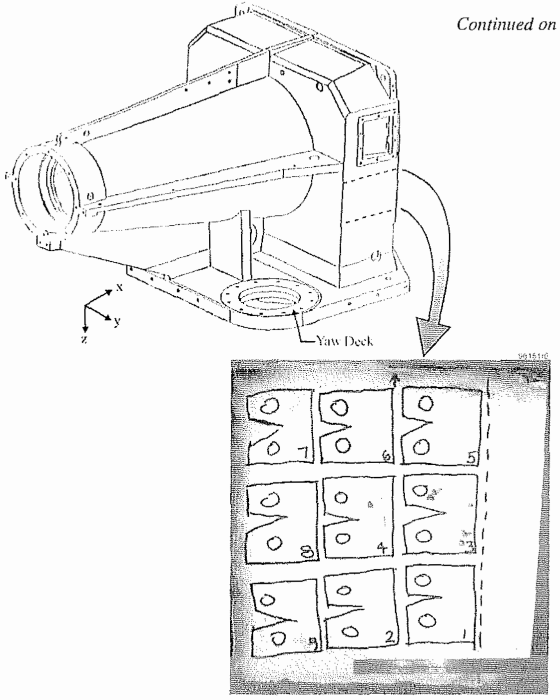

Figure 3. Schematic of transmission housing showing location from which fracture mechanics crack growth specimens were obtained

(grinding to remove surface imperfections, and shot peening). Additional testing was performed to develop fatigue curves for the proposed remedies.

Results and Recommendations

The results of the evaluation are illustrated in Table 1. It demonstrates that the observed incidences of fatigue failure are consistent with analytical expectations for as-cast housings operated on the full power curve (410 KW). The 99th percentile failure prediction is only 0.15 years (i.e. the first failure in 100 units is predicted to occur in less than this time) and the mean predicted time to failure is 1.3 years. On the other hand, if the units were operated on a reduced, 360 KW power curve, the first failure time and mean time to failure are 1 year and 7.9 years, respectively. The predicted failure times improve substantially if the units are grind improved or peened. Grinding improves the fatigue life to marginally acceptable levels (2.9 years to first failure and 40 year mean time to failure), **while shot peening improves the life to acceptable levels (578 years to first failure and essentially infinite mean failure life), at full power (410 MW) operation.**

TABLE 1 - Results of Statistical Damage Fraction Analysis

Assumed Material Condition	Predicted Times to Failure, Years			
	360 KW Operation		410 KW Operation	
	99th Percentile[1]	Mean[2]	99th Percentile[1]	Mean[2]
As-Cast	1.0	7.9	0.15	1.3
Ground	17.9	242	2.9	40
Shot-Peened	∞	∞	578	∞

Notes: 1. First failure in 100 units predicted at 99th percentile time.
2. Failure of 1/2 of units predicted at mean time.

Conclusions

On the basis of the analyses and results described herein, the wind field operator was able to operate the turbines at reduced power (360 MW) for the remainder of the current wind season, with appropriate remuneration from the manufacturer for lost power costs. A procedure and vendor for field shot peening of critical regions of the housings were subsequently qualified, and a long term implementation plan for this remedy was developed, in order to achieve acceptable levels of risk under full power operation.

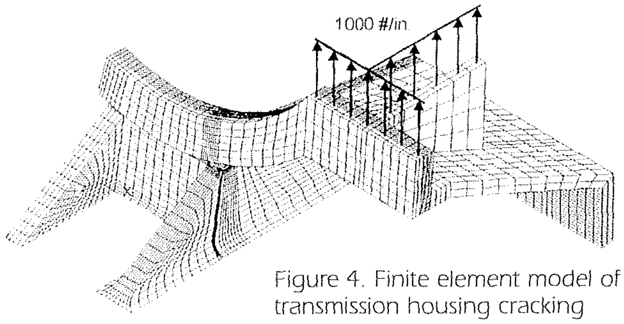

Figure 4. Finite element model of transmission housing cracking location

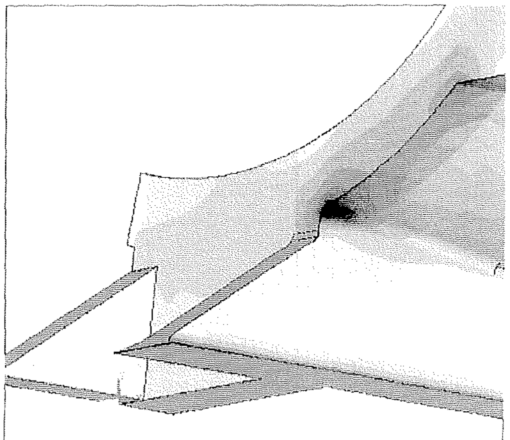

Figure 5. Stress distribution resulting from finite element analysis

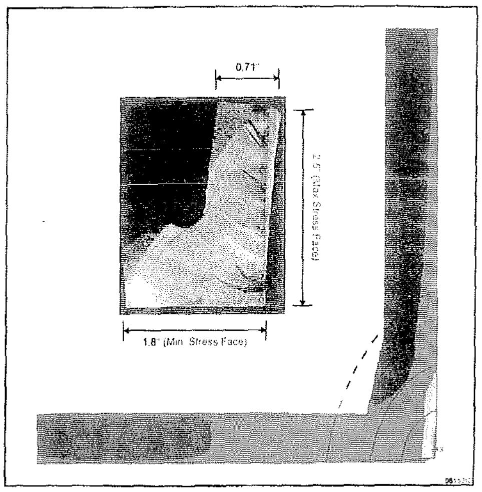

Figure 6. Horizontal section of finite element model through crack location with fracture mechanics model superimposed

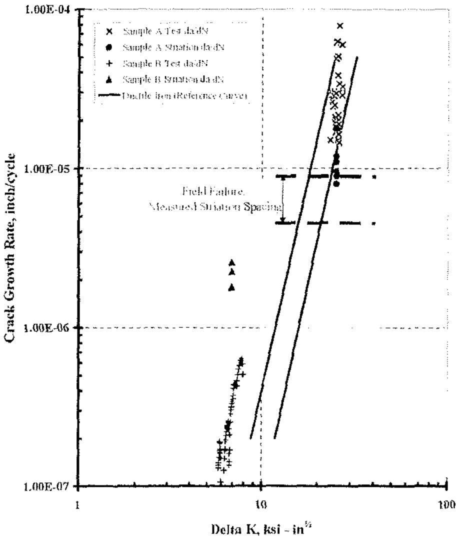

Figure 7. Fracture mechanics crack growth test results and correlation with measured striation spacing

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For more information, visit www.structint.com or email Peter Riccardella at priccard@structinit.com.