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STRAIN MEASUREMENT ON THE RUNNER OF A HYDROELECTRIC TURBINE

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Strain Measurement on the Runner of a Hydroelectric Turbine

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Abstract: Twelve strain gages were installed on the 10-m-diameter runner of Unit G-23 (700 MW) at Grand Coulee Dam, Third Powerhouse. The gages were located on both the pressure and suction sides of blades 8, 9 and 10 and were positioned in order to measure strains near the trailing edge to crown transition of the runner. This is an area where cracks have previously been discovered on Units G-22 and G-23. Four channels of RF (radio frequency) transmitters were used to record the response of four strain gages at a time while the unit was in various operating conditions. A fixed antenna was placed around the turbine shaft and connected to a receiver. The receiver processed the incoming strain gage signals and they were recorded with a digital audio tape recorder along with the unit speed, wicket gate position and load condition.

Strain gage installation techniques are discussed, especially the waterproofing and securing of the lead wires. Each RF transmitter was enclosed within a custom-made box which included a bridge completion circuit, adjustable balancing resistors, and the batteries which powered the transmitter. A sample of the results will be presented for illustrative purposes.

Background

Cracking of runner blades is not an uncommon occurrence in Francis turbines [Parmakian and Jacobson, 1952]. Cracks are generally found in crown-to-bucket and band-to-bucket transitions and are caused by periodic stresses that fatigue the material [Powell, 1958], defects in the original castings and welds, or sudden loading from debris or misoperations. In most cases, periodic weld repair, or stop drilling at the end of the crack to arrest its growth is sufficient to extend the life of the runner. Changing the blade geometry or adding stiffeners between blades may have to be used if the cracking is a result of excitation of the natural frequency of the blade.

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Measurement of actual stress levels [Haslinger and Quinn, 1987] can be an important factor in formulating a solution to a blade cracking problem. Recent trends have used finite element modelling [Degnan, et al. 1986] to analyze this complex loading case; however, without verification from actual measurements, some judgement in the interpretation of the results needs to be used.

Introduction

The Grand Coulee Third Powerhouse features six vertical-shaft Francis turbine-generators outputing a total of 3,900 MW. Unit G-23 is one of three units rated at 700 MW @ 87-m head. The runners have 15 blades and operate at a rotational speed of 1.428 Hz. In August 1990, project personnel identified 19 cracks on Unit G-23 and a similar number on Unit G-22. Due to the relatively sudden development of some of the cracks and the consequences of losing a piece of a bucket on the 10-m-diameter runners, the decision was made to attempt to measure actual stresses on the runner during different operating conditions.

Operational History

Unit G-23 went into operation in 1979. Operationally, the turbine has been relatively free of problems. Periodic weld repair of cavitation damage on the runner has been needed. Inspection in 1990 revealed many cracks, and these were weld repaired. Subsequent inspections have revealed new cracks. To date the unit has operated more than 60,000 hours. Prior to 1988, there were problems in maintaining tailwater depression during the synchronous condensing mode. Having the tailwater come back up on the motoring runner causes a large instantaneous increase in loading and torque. This problem has been fixed and yet cracks still continue to appear and grow.

Approach

Instrumentation: We decided to directly measure strains present at the areas of interest under a variety of operating conditions. The measurement scheme included mounting four strain gages on three adjacent blades. On each blade, two gages were mounted on the pressure side and two on the suction side. They were located near the trailing edge to crown transition, just at the point of tangency of the weld between the crown and blade. The uni-axial gages were mounted with their sensing direction perpendicular to the crown of the runner and centered on lines 6.35 mm and 101.5 mm from the trailing edge, figure 1. Prior to installation, the runner was sandblasted to remove paint in all areas where gages and wiring were to be attached. We mounted the gages on the prepared runner surfaces using a low-power spot welder. The gages had an active length of 12.7 mm and were 6.35 mm wide.

From the beginning, we realized that it would be a tremendous challenge to strain gage this runner and collect data during full load and flow conditions (800 MW, 85-m head and 850 m^3/s discharge). The gages were waterproofed in the following

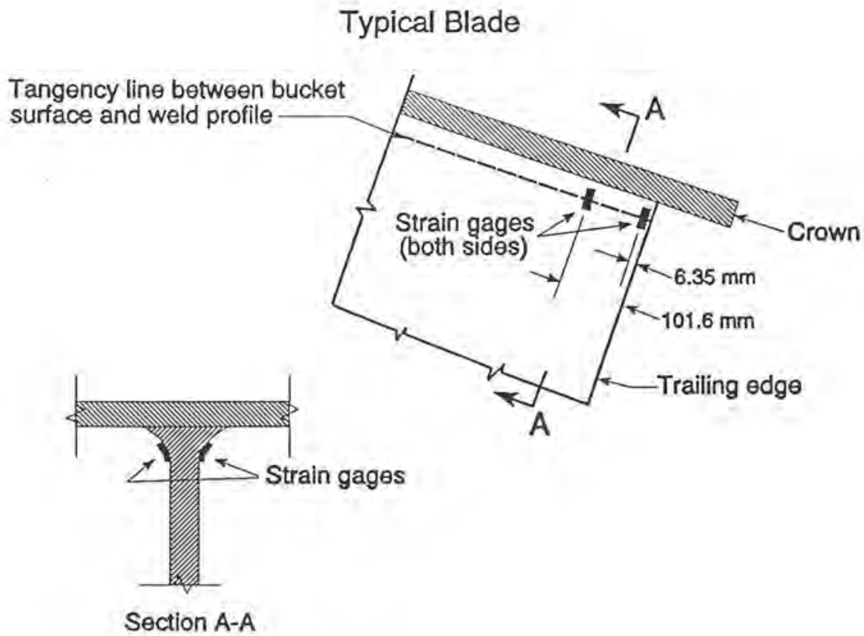

Figure 1: Location of strain gages.

manner. A layer of Teflon film was placed over the solder connections, then a patch of bituthane covered the entire gage. The lead wires were worked into the patch material. Aluminum tape was placed over the entire patch and lead wires and the edges of the tape were sealed with two coats of brushable nitrile rubber. In the gage area, we then applied a coat of aluminum putty. This putty is a two-part, epoxy-based coating which can be machined when dry. The aluminum putty was ground and sanded to a smooth surface, figure 2.

Connecting, routing, and waterproofing the signal wires was the next step. The wiring was passed from the runner into the center of the hollow 3.35-m-diameter shaft through a heater hole in one of the coupling studs. A half coupling was welded to the shaft side of the heater hole and a pressure-tested, pass-through connector was tightened in place. The wires going to the transmitters were then passed through a 19-mm-diameter hole which had been drilled through the shaft into the turbine pit area. At the strain gage end, wires were secured initially with thin stainless steel straps tacked down with the spot-welder. The final solder connections were made and the wires were taped down using aluminum tape. The tape edges were sealed with brushable nitrile rubber. At this point, all the gages were tested at the termination point in the turbine pit, and all were in working condition.

The final treatment to the wires and gages consisted of applying a two-part, epoxy-based brushable ceramic compound. This coating has a relatively long curing time; however, it dries to a very smooth finish. This brushable ceramic was used to coat all of the wiring and gage areas, figure 3.

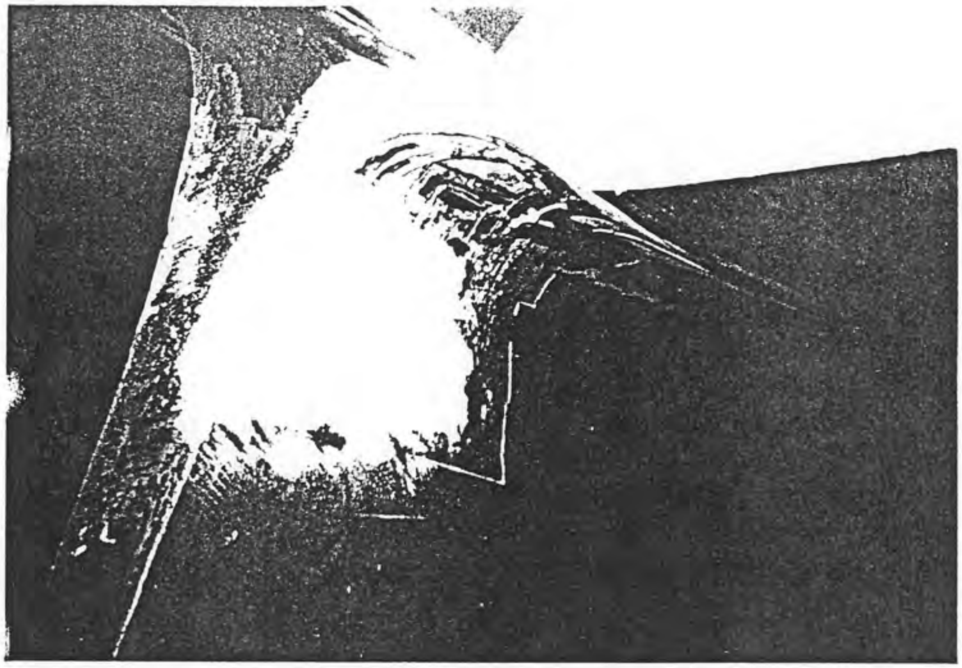

Figure 2: Gages with aluminum putty coating in place.

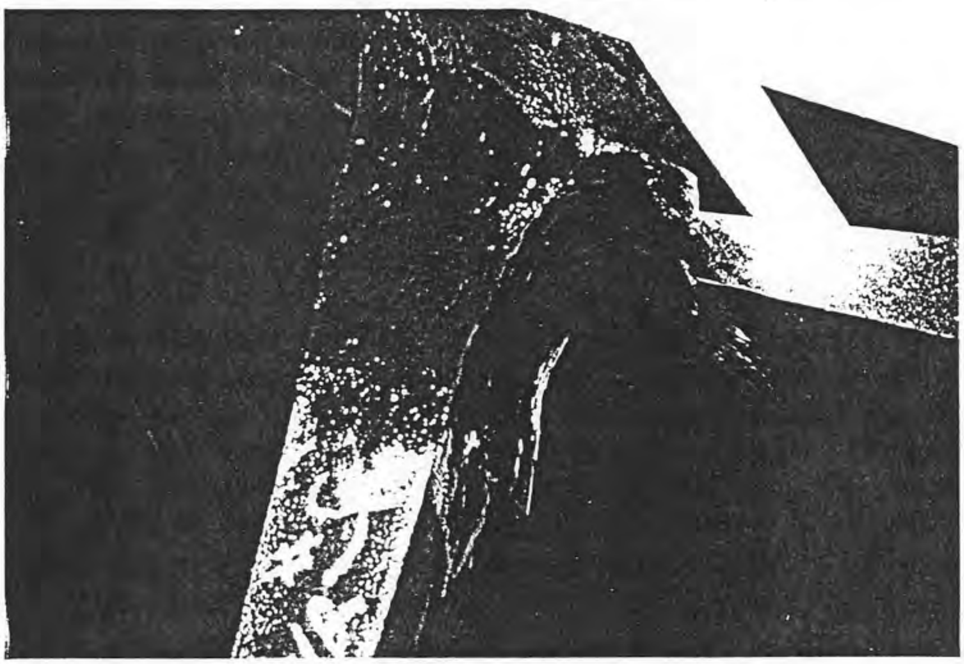

Figure 3: Final coating of brushable ceramic epoxy-based coating.

The telemetry system we used was manufactured by ACUREX (now Wireless Data Corporation). It contained four channels of signal conditioning. The receivers can be tuned to signals anywhere in the FM radio band between 88 and 108 MHz. The signal conditioning cards process strain gage signals from d.c. to 1000 Hz. The output level is adjustable from 1.0- to 3.0-V peak-to-peak full scale. The transmitters are pretuned and designed to operate with sensors in a Wheatstone bridge circuit. The input ranges of the transmitters when using a bridge circuit with one active element are jumper selectable in ranges of 0-500, 0-1500, or 0-5000 $\mu\epsilon$. The minimum bridge impedance is 350 Ω. The transmitters can be battery powered (2.7V d.c.) or energized using a separate induction coil with a voltage regulator.

We constructed four enclosures for the transmitters which included the batteries for excitation and the bridge completion circuitry. The boxes were bolted to brackets which had been tack-welded to the shaft. The front cover had a terminal strip where the strain gage lead wires were attached to the bridge completion circuit. A variable resistor allowed us to balance the bridge circuit easily. Once powered up, the bridge circuit output is transmitted by RF over a small antenna attached to the transmitter. The receiving antenna was mounted around the perimeter of the shaft, at the same level as the transmitter boxes. The receiving antenna was configured in a "folded tee" and connected to the receiver module which housed the four signal conditioning cards.

The ACUREX telemetry system is significantly different from conventional telemetry in the method of signal transmission. Standard telemetry systems use relatively high power and a high gain antenna system (allowing long distance transmission). This system uses very low power and is generally operated in mechanical situations where high gain antennas are not appropriate. Usually the operating distances are small enough that capacitive or magnetic coupling is used rather than the typical electromagnetic carrier coupling. We used capacitive coupling between the small antenna on the transmitter and the "folded tee" antenna. At the rotating speeds of most hydropower units, continuous data transmission (no signal drop out) is possible.

In addition to the four channels of telemetry, we also recorded unit speed, wicket gate position, and electrical load. The feeds for these inputs were provided by permanent sensors at the powerplant. All signals were recorded on a TEAC RT-111 Digital Audio Tape recorder. Figure 4 shows a cutaway of the turbine, showing the general strain gage and transmitter locations.

Testing: Approximately 2 weeks after the installation was completed, we returned to Grand Coulee to perform the testing. The test plan included collecting data from four strain gages simultaneously, i.e., blades 8, 9, and 10. We wanted to record strain levels for several different operating conditions: speed-no-load, 120 percent speed-no-load, loads up to 800 MW, a load rejection, and synchronous condensing mode.

Results and Discussion

The testing took place over 2 days. Since the unit had been out of service for several weeks for scheduled maintenance, the standard checkout testing was completed prior to the beginning of our tests. These tests included a slow-roll with

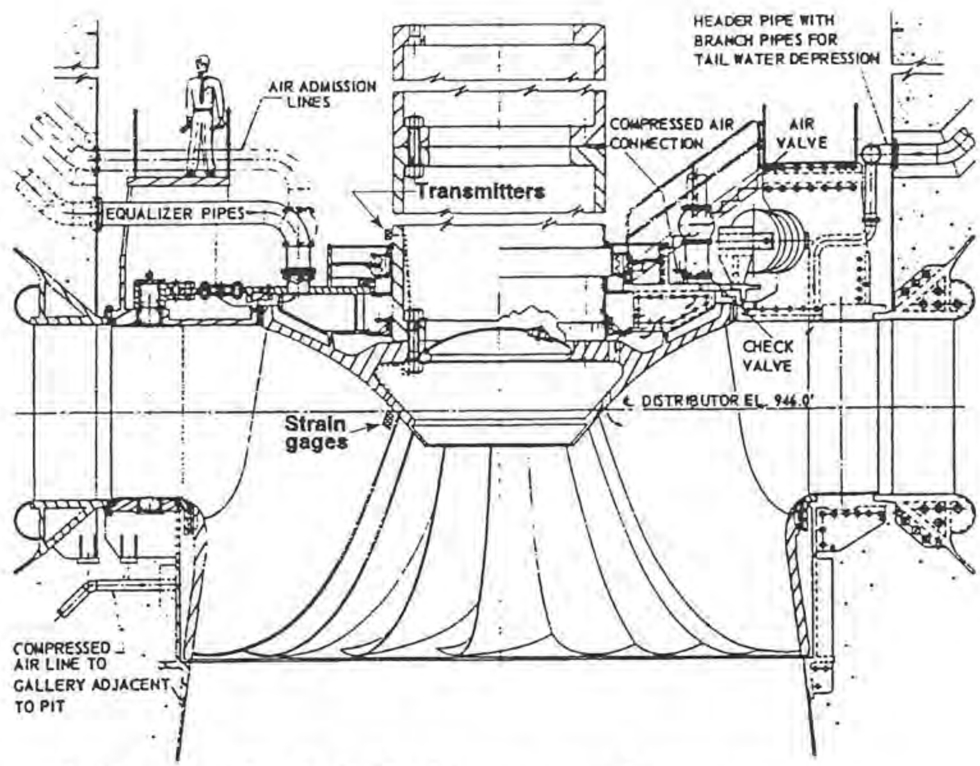

Figure 4: Cutaway of Unit G-23, showing general arrangement.

personnel located inside the air housing of the generator to observe the unit rotation. After some minor adjustments, the unit was brought up to speed in 25-percent increments. During these checkout tests, our instruments were also checked out and were operating well. The transmitters had been set to the 500 $\mu\epsilon$ range with full scale bridge output set at 2.5 V using shunt calibration.

The first day of testing resulted in recording speed-no-load and 120-percent speed conditions for gages 1-4 on bucket No. 8. The day was not without some excitement as a secondary relay was tripped by the overspeed and initiated an emergency closure of the penstock coaster gate. While waiting for the penstock to refill, we changed the gain to the 1500 $\mu\epsilon$ range as the speed-no-load strain levels were higher than we expected. We then tried to begin the load portion of our test but could not successfully load the unit. A governor problem was discovered and the remainder of our tests was postponed until the following day.

Upon arriving at the powerhouse the next morning, we noticed that gage No. 1 was no longer functioning. We decided to switch to blade No. 9 (gages 5-8) so that an entire instrumented bucket would be used during the test. We connected gages 5-8 to the transmitters and balanced the bridge circuits. We were not able to balance gage 5. We balanced the remainder of the gages and proceeded. The unit was brought up to speed and then load was applied. Gage output was inconsistent which indicated that there probably was damage occurring to the gages or wiring.

After the first loading test up to 800 MW, only one strain gage remained in operating condition. This was gage No. 10 (pressure side) on blade No. 10. The test sequence for this gage involved speed-no-load, synchronous condensing, loads up to 800 MW and a load rejection. The gage remained in working condition throughout the entire test. Samples of test data are shown in figure 5a and b.

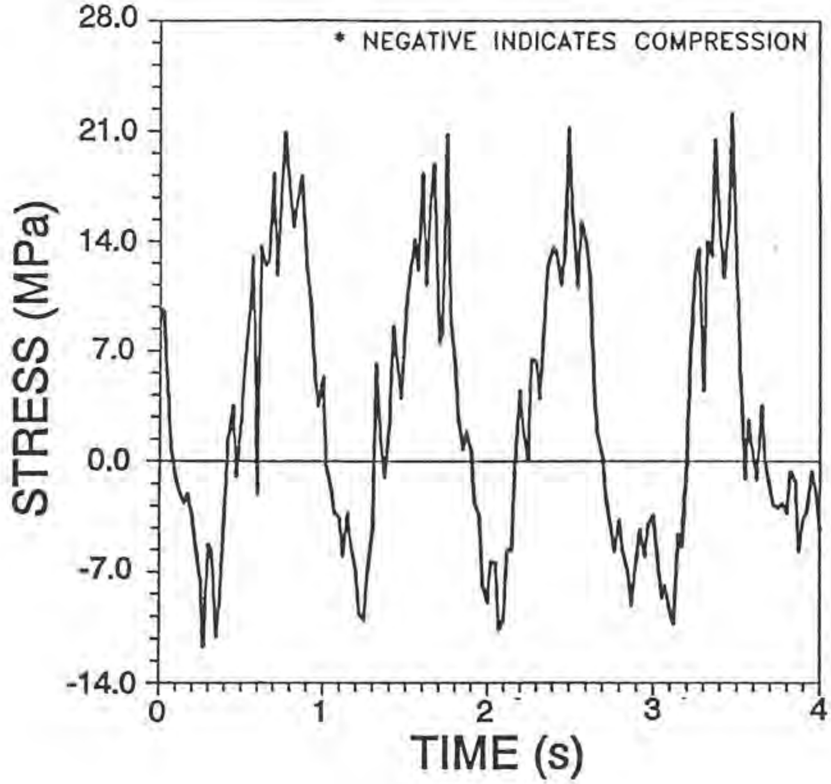

Figure 5a: Time series of stress levels on gage 10 at a 40-percent wicket gate position (note periodic draft tube surge).

Following testing, an inspection of the runner revealed that almost all signal wires had been ripped off by the flowing water. The gages themselves were all intact as the aluminum putty remained in place, figure 6. Although only one gage survived the entire test, critical data were obtained to allow prediction of crack formation and propagation.

The collection of data from rotating machinery is becoming a more straightforward exercise with the use of small commercially available telemetry systems. There is no longer the need for slip rings or expensive induction systems. However, many of the same old problems remain in the installation of the sensors, especially in a submerged environment. The dynamic forces induced on the sensors and associated wiring are substantial. Care needs to be taken in the protection of these features by coatings or mechanical means which will survive the dynamic forces.

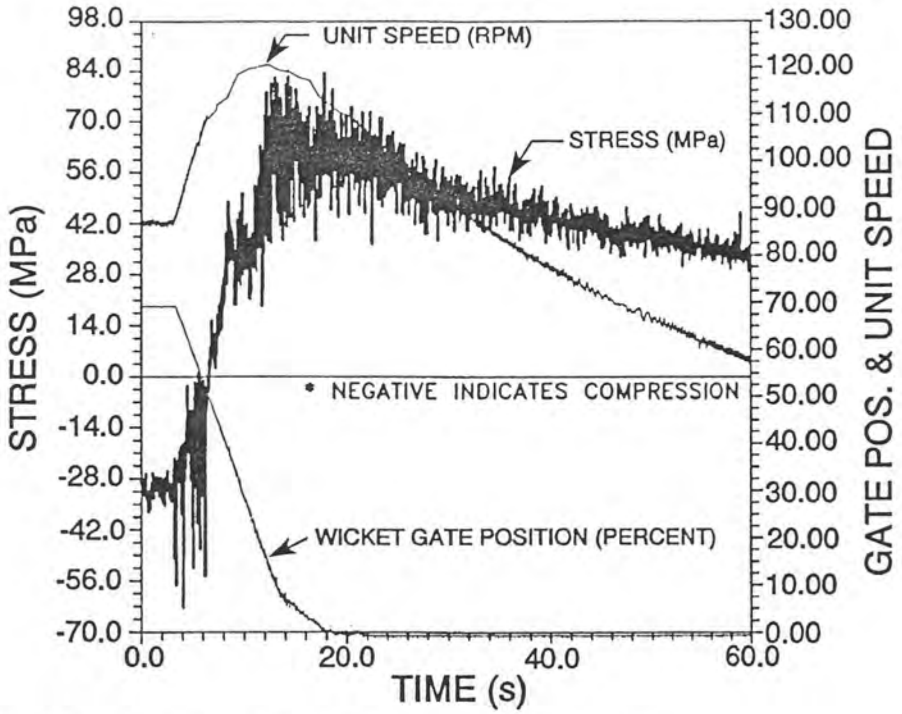

Figure 5b: Output of gage No. 10 during a load rejection.

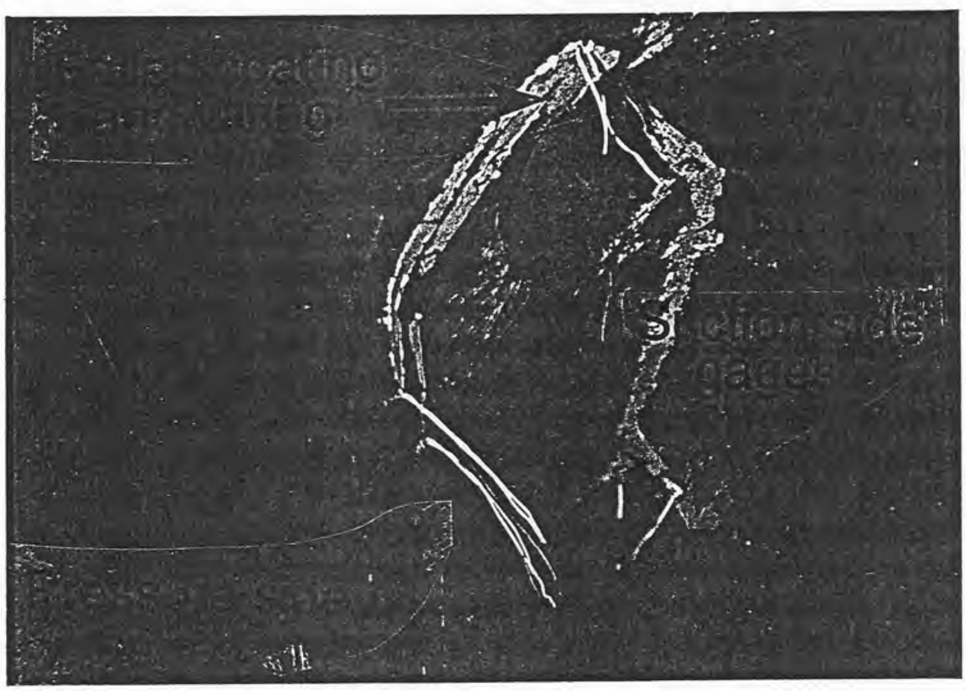

Figure 6: Strain gage installation after the test. Note gages are still intact; however, the ceramic coating failed causing failure of the lead wires.

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