RECLAMATION

Managing Water in the West

Extending the Useful Service Life of Wire Hoist Ropes using Nondestructive Testing

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Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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14. ABSTRACT

The wire hoist ropes at Shasta Dam exhibited corrosion on the surface as noted during routine visual inspection. In accordance with ANSI B77.1 and US Code of Federal Regulations 30 CFR 30 the ropes would require replacement as soon as possible. The wire ropes were replaced in 2012 and eleven wire rope sections were shipped to the Denver office. This research proposal involved having electromagnetic NDT performed on the rope sections to determine the condition of the wire ropes and identify problems or weak areas. Destructive testing of the wire rope sections were performed after the NDT completed. Testing was conducted for sections of rope exposed to multiple exposure conditions including atmospheric, fluctuating immersion (waterline) and full immersion. The test specimens were fitted with 100% efficient sockets, and underwent tensile testing until failure. Comparison of the test results from the destructive testing and the results of the NDT was done to determine the effectiveness of the NDTmethod.

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Executive Summary

The Materials Engineering and Research Laboratory (MERL) conducted a study to investigate the Magnetic non-destructive testing (NDT) method to predict, more accurately, the remaining service life on wire ropes. The study focused primarily on determining if the magnetic NDT method was a reliable determination of wire rope functionality or structural condition.

NDT of wire ropes allow testing on in-service ropes without permanently damaging them. NDT can provide a methodology that will help determine when to remove wire ropes from commission and decrease the frequency of possible unnecessary replacements, significantly decreasing costs over time. There are a number of non-destructive methods presently in use for testing wire ropes that allow for strength assessment and more accurate service life prediction. Our study chose to focus on the Magnetic NDT method.

Based on the results and issues presented, the following conclusions were drawn:

- An NDT testing technique should accompany visual inspection to gauge the condition of the interior, non-visible regions of the wire rope.
- Testing should be conducted on full length ropes, not on small sections, to gauge its entire condition.
- It was not feasible to draw accurate conclusions identifying if this method works for estimating lifetime. The ropes were too damaged and there was not a baseline for comparison.
- Magnetic NDT testing would be better utilized if testing occured at regular intervals and started at the beginning of a ropes life. These ropes were so far along in the degradation process that the data was not helpful.
- More assessments are needed using newer ropes to ascertain the feasibility of the Magnetic NDT method.
- There are a number of other methods that can be employed to determine the condition of wire rope. They should be evaluated for effectiveness.
- Under tension testing, the corroded wire ropes still maintained a safety factor of 3.5:1 as compared to operational loads, suggesting that the Magnetic NDT test results did not make a good comparison in terms of remaining service life.

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Introduction

The Materials Engineering and Research Laboratory (MERL) conducted a study to investigate the Magnetic non-destructive testing (NDT) method to predict, more accurately, the remaining service life on wire ropes. The study focused primarily on determining if the magnetic NDT method was a reliable determination of wire rope functionality or structural condition.

NDT of wire ropes allow testing on in-service ropes without permanently damaging them. NDT can provide a methodology that will help determine when to remove wire ropes from commission and decrease the frequency of possible unnecessary replacements, significantly decreasing costs over time. There are a number of non-destructive methods presently in use for testing wire ropes that allow for strength assessment and more accurate service life prediction. Our study chose to focus on the Magnetic NDT method.

Background

The wire hoist ropes for some of the gates on the Shasta Dam Temperature Control Device exhibited corrosion on the surface as noted during routine visual inspection. In accordance with ANSI B77.1 and US Code of Federal Regulations 30 CFR 30 the ropes require replacement as soon as possible. In 2009, the corroded wire ropes underwent non-destructive testing to determine the extent of corrosion and loss of strength. The report from the contractor indicated that the ropes were still within the factor of safety for use. However, due to the currently used standards, the Reclamation report issued in 2009 recommended replacement of the ropes as soon as possible. Magnetic NDT testing was performed by Silver State Wire Rope in 2009 at Shasta Dam preceding the recommendations to remove the ropes from service. In 2012, the wire ropes were replaced and eleven wire rope sections were shipped to the Denver office. Magnetic testing was then performed on shorter sections of the Shasta Dam wire rope at the Silver State Wire Rope facility. The ropes were originally installed during construction in 1993; therefore, they were at their lifetime service limit of 15-20 years [2].

Many Reclamation sites utilize wire ropes for operating gates that are approaching the end of their expected life cycle (~15-20 years). NDT could potentially yield results that suggest that the wire ropes are still suitable for use, while other criteria recommend replacement. If deemed more pertinent, the utilization of NDT could prevent premature replacement of ropes, therefore extending the usable life of the ropes, and reducing capital expenditure. Reclamation will be able to improve dam safety by utilizing NDT to examine wire ropes for personnel elevators, gate hoists, and the various cranes throughout Reclamation.

Testing

Testing was conducted for sections of rope exposed to multiple exposure conditions including atmospheric, fluctuating immersion (waterline) and full immersion. The testing involved having Magnetic NDT performed on the rope sections to determine the condition of the wire ropes and identify problems or weak areas, such as broken wires. Destructive testing of the wire rope sections were performed on a new wire rope from Silver State Wire Rope along with two corroded sections of wire rope from Shasta Dam. The test specimens were fitted with spelter sockets on both ends, and underwent tensile testing until failure.

Examination of the Magnetic NDT results along with comparisons of the tension test results for the old and new wire rope were used to identify the condition of the old corroded wire ropes.

Discussion

Steel wire ropes have a disadvantage in that only the outer strands of the rope can be visually inspected. The metallic rope core itself accounts for about 50% of the wire rope’s area and is surrounded by a second layer of wire rope, as shown in Figure 1. The wire ropes used at Shasta Dam are constructed of 6 outer strands consisting of 19 wires each, along with a steel core consisting of 7 bundles of 7 wires each. In Figure 1 corrosion has begun to damage many of the outer and inner strands. The only wires that can be visually inspected on a wire rope in service are the outer wires. Visual inspection of the interior stands is not possible without destructively taking apart the rope. As shown in Figure 2, when the wire rope was unraveled, the undetectable inside region was so damaged that it broke. This damage would go undetected if a visual inspection was the only method employed.

Figure 1: Inside Construction of a Wire Rope

Figure 2: Broken Interior Strands of Wire Rope

Currently, a wire rope is given a lifetime estimate.. Once the wire rope has reached its lifetime estimate, the wire rope is replaced, whether it needs to be or not. There are many NDT methods that allow for testing of remaining lifetime without having to unnecessarily pull a wire rope from service. Our focus was on Magnetic NDT of wire ropes from Shasta Dam. Other methods are described in appendix A.

Magnetic NDT

The principle behind Magnetic NDT is the detection of changes in an induced magnetic field. As seen in Figure 3, a set of magnets are moved along the wire rope and the magnetic flux (total magnetic field passing through a given surface area) changes based on the presence of damage, loss of rope, and corrosion pits. At areas of damage, flux leakage occurs and is picked up by the sensor [1]. Whenever the flux decreases, it is an indicator of some type of damage to the rope: loss of wire, pit corrosion, etc. [1].

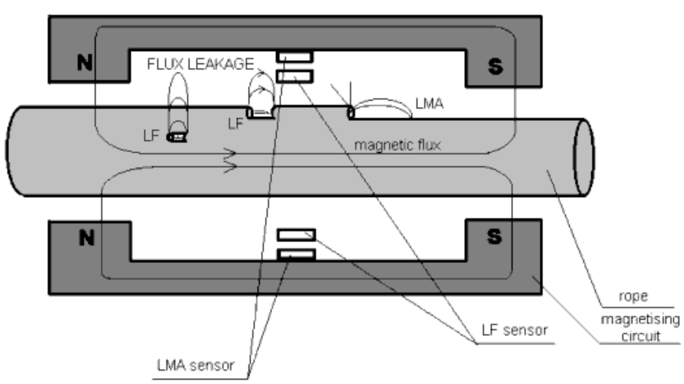

Figure 3: Magnetic NDT Schematic

The primary disadvantage in using this method is the limitation of using only ferromagnetic steel ropes. This method will not work with any other material.

This method also generally needs to be accompanied by visual examination, as sometimes groups of wire breakage in close proximity to each other can generate a complex signal.

Magnetic NDT works by placing permanent magnets longitudinally to magnetize the rope as it passes through the sensing head. Direct current (DC) excitation coils are used. Both local fault (LF), also called low flow, and Loss of Metallic Cross-Sectional Area (LMA) sensors can be used individually or together depending on the desired testing information [1]. Simplified auxiliary testers, as shown in Figure 4, use signals to detect localized flaws. Computer recordings, shown in Figure 5, are also used to help determine loss of cross sectional area. A constant magnetization of the rope must be strong enough to create magnetic saturation of the rope. This method is portable and can be used in the field.

Figure 4: Magnetic NDT Testing of Shasta Dam Wire Rope

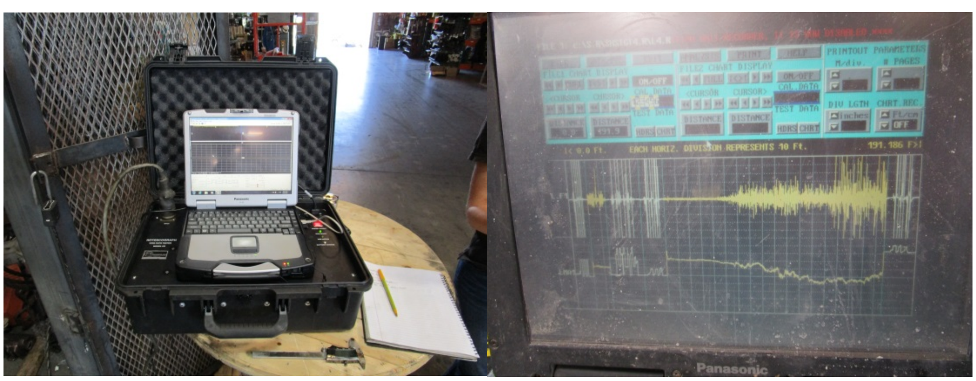

Figure 5: Computer Recording of Magnetic NDT data

During the Magnetic testing at Shasta Dam in 2009, one of the issues identified during the inspection was that the condition of the ropes varied widely along the length of the rope. The wire ropes were sent to Silver State Wire Rope in 2012 for re-testing of the short sections showing varying degrees of damage. The wire rope test sections used were too short to conclusively say if the Magnetic NDT method was a reliable method to use. Because there is such large variability along the length of a full rope, short sections are not representative of the full rope condition.

Magnetic NDT scans during ideal conditions can identify a lot of useful information. Figure 6 depicts the scan result from a new wire rope tested by Silver State Wire Rope. The flat line gaps between testing segments is where the testing head was removed from the wire rope and retesting of the same wire rope was conducted. This checks for reproducibility in the scans. When reading scans, the LF and the LMA coincide. The LF section (top scan box) will typically have noise associated with corrosion products and wear. The LMA section (bottom box) will generate dips and spikes that coordinate with the LF to indicate if broken wires are present. Using the values in the scans a loss of breaking strength can be ascertained. In order to determine loss of breaking strength (loss) of the wire ropes based on this NDT test method the following relationship is used:

$$"loss" = \sqrt{\frac{LF(worst)}{LF(best)}} xLMA(worst)$$

The LF worst and LF best are pulled from the graph and used with the coinciding LMA value to obtain a theoretical loss in breaking strength. Criteria listed in the U.S. Code of Federal Regulations CFR 30 allows for a loss of breaking strength up to 10% before replacement is required.

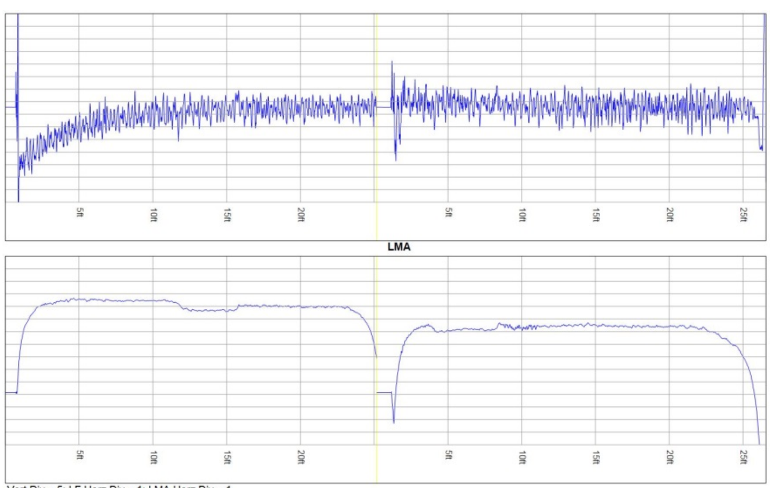

Figure 6: Scan of New Wire Rope

The scans in Figure 7 show examples of some issues that can show up on a scan. In the scan of the new wire rope it can be noted that the noise is fairly low compared to the scans in Figure 7. In fact, the scans in Figure 7 have so much noise that reasonable assumptions can no longer be made. The dips and spikes no longer have meaning and the data can not be interpreted to determine internal damage to the wire ropes. Based on visual inspection of the tested wire ropes, the reason for such large noise is the accumulation of corrosion products. The significant amount of corrosion of the rope masks the signal of any internal wire rope damage.

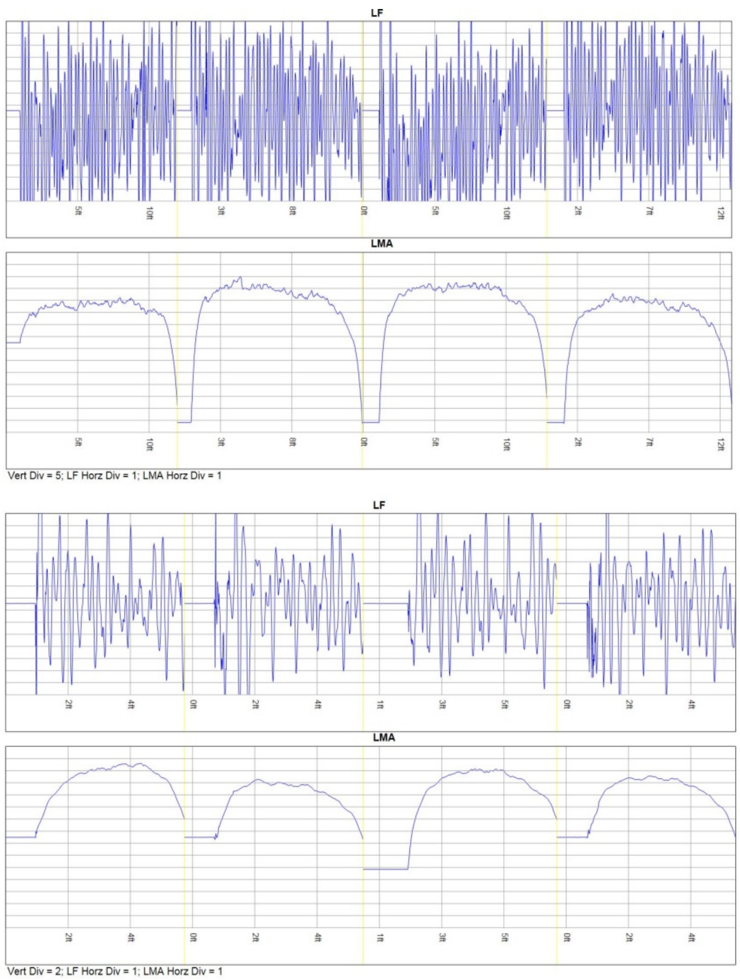

Figure 7: Scans of Damaged Shasta Dam Wire Rope a) Lower Gate 2 b) Pressure Relief Gate 5

Based on the Magnetic NDT scans performed by Silver State Wire Rope we are unable to draw any conclusions on the conditions of the wire rope. It would be more qualitative if the wire ropes were assessed regularly using this method beginning shortly after installation. This would provide a baseline for comparisons and a better interpretation of results. The wire ropes at Shasta Dam had not been previously tested using the Magnetic NDT method and therefore provided no baseline for comparison.

Tension Testing

Tension tests were performed on two of the corroded Shasta Dam wire ropes along with a new wire rope from Silver State Wire Rope. All the ropes were approximately the same thickness and length and had spelter sockets on each end. Figure 8 shows the testing set up using the Instron 3MN Universal Testing Machine. Figure 9 shows the new wire rope during the break point. Visually, the rope can be seen separating as well as sparking from the individual strand breaks against the plexiglass shield. The plexiglass shield used in the first test failed due to impact from the wire rope. Subsequent tests used a thicker shield, as shown in Figure 9.

Figure 8: Pre-testing initialization of wire rope on Instron 3 MN Universal Testing Machine

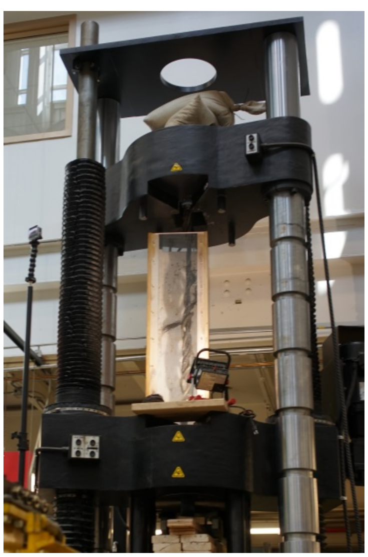

Figure 9: New wire rope break during test

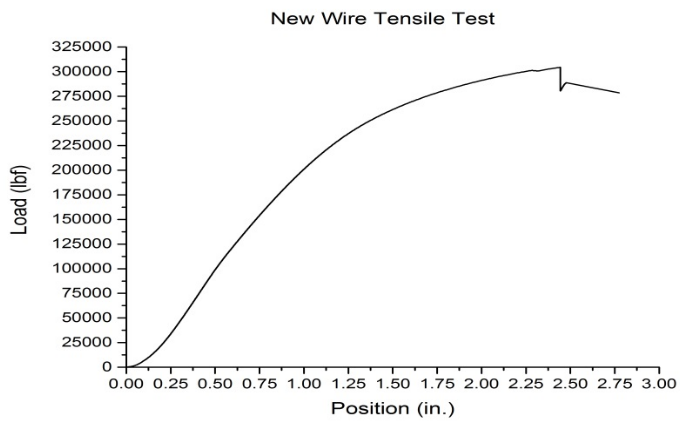

Figure 10: Tension test results for new wire rope

Figure 11: Broken new wire rope after testing: a) Strand un-winding and b) Severed ends

Results in Figure 10 show that the ultimate tensile strength of the new wire rope was 304,384 lbf. The manufacturer stated that the ropes had a strength of 250,000 lbf. Testing was performed at a loading rate of 50,000 psi per minute. The new wire rope failed by a mechanism of un-winding as well as individual strand breakage as seen in Figure 11.

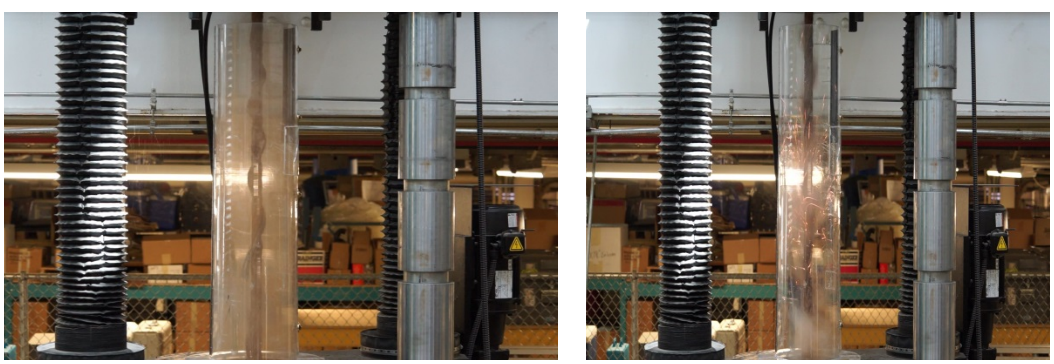

Figure 12: a) Breaking point during tension test of corroded wire rope and b) Sparks due to individual strand breaks.

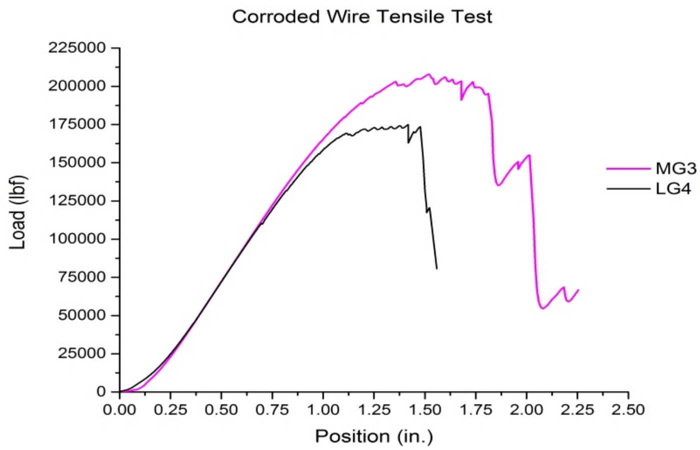

Figure 13: Tension test results of corroded wire rope

Results in Figure 13 show that the ultimate tensile strength of the corroded wire ropes was 174,992 lbf and 207,840 lbf. The corroded wire rope failed by individual strand breakage as seen in Figure 14, as opposed to the mechanism involved in the new wire rope. It should be noted that a typical design safety factor is at least 5:1 for wire ropes. At failure, even the most corroded rope achieved a safety factor of 3.5:1. This assumes an in-service working load of 30,000 lb for each of the wire ropes based on calculations under normal balanced lifting. A loss in strength of 10 percent is also assumed due to bending of the ropes at the drums/sheaves as well as galvanizing.

Figure 14: Broken corroded wire rope after testing

Under tension testing, the most corroded wire rope still maintained a safety factor of 3.5:1 as compared to operational loads. Magnetic NDT suggested that the ropes were too badly damaged to remain in service, but also did not contain any comparable data. We were unable to establish a strong correlation between the tension test results and the Magnetic NDT results.

Conclusions

Magnetic NDT and destructive tension testing were conducted on the Shasta Dam wire ropes. Based on the results and issues presented, the following conclusions may be drawn:

- An NDT testing technique should accompany visual inspection to gauge the condition of the interior, non-visible regions of the wire rope.
- Testing should be conducted on full length ropes, not on small sections, to gauge its entire condition.
- It was not feasible to draw accurate conclusions identifying if this method works for estimating lifetime. The ropes were too damaged and there was not a baseline for comparison.
- Magnetic NDT testing would be better utilized if testing occured at regular intervals and started at the beginning of a ropes life. These ropes were so far along in the degradation process that the data was not helpful.
- More assessments are needed using newer ropes to ascertain the feasibility of the Magnetic NDT method.
- There are a number of other methods that can be employed to determine the condition of wire rope. They should be evaluated for effectiveness.
- Under tension testing, the corroded wire ropes still maintained a safety factor of 3.5:1 as compared to operational loads, suggesting that the Magnetic NDT test results did not make a good comparison in terms of remaining service life.

References

[1] A. M. Ritt, "Report of Issue Evaluation for Shasta Dam TCD Gate Hoists-Wire Rope Corrosion," 2009.

[2] K. Zawada, "Magnetic NDT of Steel Wire Ropes," 1999.

[3] J.-M. Nussbaum, "High Resolution Magnetic Induction Wire Rope Test. Part 2: Detection of Broken Wires in Wire Ropes by Analysis of the Scatterfield," Univeristy of Stuttgart, Germany.

[4] R. Varreet, "A new method for detecting wire rope defects," in *OIPEEC Conference*, Athens, 2006.

[5] L. Hui, L. Chengming, L. Dongsheng and O. Jinping, "Monitoring and Failure Analysis of Corroded Bridge Cables under Fatigue Loading Using Acoustic Emission Sensors," *Sensors*, 2012.

[6] J. Kurtz, L. Laguerre, F. Niese, L. Gaillet, K. Szielasko and F. Treyssede, "NDT for Need Based Maintenance of Civil Infrastructure – FilameNDT a Franco-German Project for Monitoring and Inspection of Bridge Cables, Ropes and Pre-Stressed Elements," in *Civil Structural Health Monitoring Workshop (CSHM-4)*, Berlin, Germany, November 6-8, 2012.

[7] A. T. Ciolko and H. Tabatabai, "Nondestructive Methods for Condition Evaluation of Prestressing Steel Strands in Concrete Bridges," Construction Technology Laboratories, Inc., Skokie, IL, 1999.

[8] WireTech World, "Non-Destructive Testing: Means of Inductive Heat-Flux Thermography," 2015.

[9] Silver State Wire Rope, "NDT Wire Rope Inspection Report," Las Vegas, NV, 2009.

[10] H. R. Weischedel, "Crane Wire Rope Damage and Nondestructive Inspection Methods," NDT Technologies, Inc..

Appendix A

Magnetic NDT testing was the chosen method for this investigation, but a number of other non-destructive testing methods are available.

Radiographic Testing is a testing method involving the placement of radioactive isotopes opposite an x-ray film with wire rope running through the middle of it. Patterns created by Gamma Rays on the film help determine breaks in the wire rope [4]. This method is not recommended due to the use of radioactive isotopes and health hazards associated with it.

Photographical Comparison is a testing technique used to determine if there are flaws in the outer rope. Pictures are taken using a strobe light triggered by a high-speed sensor. The high-speed images taken by a slit aperture camera from different directions are superimposed with the positive black and white image of one lay length with the negative black and white image of the next lay length [5]. One of the images is of a known undamaged strand. Damaged areas appear as white flashes on the images. Figure 15 demonstrates the camera layout and Figure 16 shows how the images are superimposed to show defects [5].

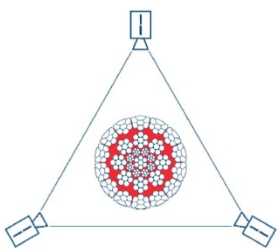

Figure 15: Camera layout for Photographical Comparison Method

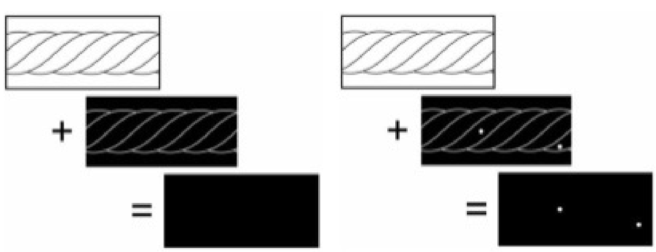

Figure 16: Superimposed images for Photographical Comparison Method

The *Acoustic Method* is a testing method that identifies deformation, fracture and fatigue damage of cables. Using scanning electron microscopy (SEM) the source of the acoustic emission can be located. The AE sensor can detect a break within a range of 30-meters and provide a high amplitude alert. The energy parameters of AE reflect the changes of material performance and its relationship with the strain energy of dislocations, fractures, and crack propagation. Fatigue fractures have three different morphological characteristics zones, including fatigue source cracking, fatigue crack, and failure as shown in Figure 17 [6].

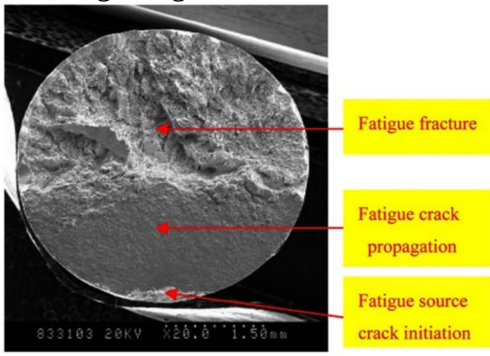

Figure 17: Scanning Electron Microscopy image of fatigue fracture

AE signals can be generated from cable fatigue damage, plastic deformation, crack formation, crack propagation, and fractures. Each damage mechanism has a unique AE signal waveform and frequency characteristic. Figure 18 displays a fatigue waveform that occurs at a low-amplitude wide pulse with a narrow frequency scale and energy concentrated at frequency bands 2 and 4, and which are located at 100 kHz to 200 kHz [6].

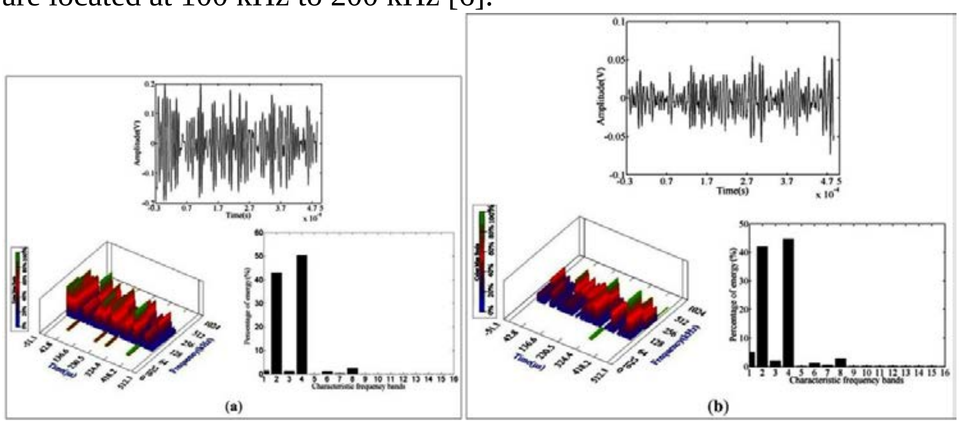

Figure 18: Fatigue Source Crack Initiation AE Waveform

Time Domain Reflectometry is a testing method where a sensor wire is applied alongside a steel reinforcement (prestressing strand) and a transmission line is created. Physical defects of the steel strand, such as abrupt pitting corrosion, general surface corrosion, and voids in grout, will change the electromagnetic properties of the line. TDR is effective in detecting, locating, and identifying the extent of damage in steel reinforcement. High-frequency electromagnetic methods such as time-domain reflectometry are time consuming, and carry radiation hazards [7]. This technique relies on the strand itself as a sensor through which high-frequency electrical pulses are sent. Impedance discontinuities caused by physical anomalies along the strand itself result in partial reflection of the pulse. Impedance is mainly a function of the inductance (L) and capacitance (C) of the line. A typical TDR sensor is a coaxial cable for which the critical TDR parameter is the impedance between the center wire and the outside shield [8].

The *Thermographic Method* utilizes cameras that measure infrared radiation emitted from the surfaces of objects, which in turn are related to surface temperatures. Subsurface data is gathered via the surface temperature because internal anomalies affect the heat flow through the body. Advantages of this method include low danger due to the equipment and speed of inspection. Due to large coverage of cameras, large horizontal defects can be identified. Disadvantages include effects on the environment from the surface temperatures; emission factor and depth of flaws are not provided [8]. Figure 19 depicts an example of an infrared test on a wire rope [9].

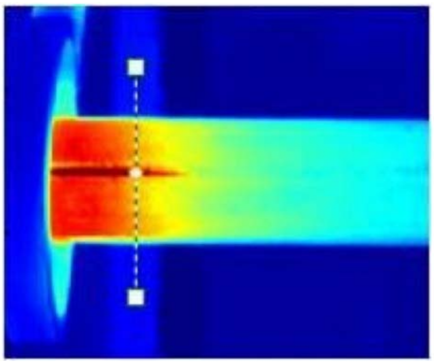

Figure 19: Infrared test for defects on a wire rope

The *Acoustic Emission* is a “passive” monitoring method where the detection system anticipates the occurrence and capture of stress wave emissions that indicate cracking, corrosion, or wire breaks. The presence of injected cement grout, as is common with stay cables, that are bonded (uncoated seven-wire strands with injected cement grout), reduces the effectiveness of acoustic emission monitoring. Acoustic emissions are more effective in unbonded cable systems, such as cable with individually greased and sheathed strands. A sensor placed at the end of a cable would receive acoustic waves that are not impeded by grout [8]. This method requires continuous monitoring for detection and capturing waveforms. Analyzation of the recorded signal is required to differentiate between real events and false triggers. Specific locations of triggers are determined by the arrival times of waveforms at different sensors [8].

The *Eddy Current Method* is a testing method based on the principle of electromagnetic induction. Flaws cause changes in the current induced by an induction coil. Eddy currents are able to penetrate into the subsurface layers including the cases where the layers are not mechanically bonded [8]. The advantage of this method in contrast to other ultrasonic methods is that mechanical contact between layers is not required. The eddy current method is capable of detecting metal loss in a 2- or 3-layer structure and can identify metal loss from metal separation. Ferromagnetic materials can only be evaluated by traditional eddy current techniques for defects over a depth of penetration of only fractions of a millimeter [8].