

Crane Wire Rope Damage and Nondestructive Inspection Methods

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Introduction

Wire ropes of a properly designed and maintained crane will deteriorate throughout their entire service life by two principal degradation mechanisms:

1. *External and internal fatigue*, caused by bending over sheaves and/or winding on drums, and
2. *Crushing*, caused by spooling on multilayer drums.

While the above types of rope deterioration can be minimized by proper crane design and rope maintenance procedures, they are deemed unavoidable and part of normal rope life.

Other rope degradation, such as excessive wear, corrosion or mechanical damage are considered problems that can be remedied by appropriate preventative maintenance procedures. Corrective measures might include rope re-lubrication, sheave alignment, etc.

This paper discusses degradation modes of crane ropes, nondestructive inspection methods and preventative maintenance procedures.

Wire rope deterioration modes

Fatigue

A wire rope subjected to repetitive bending over a sheave will develop cracks in individual wires. Broken wires develop primarily in sections that move over sheaves. Further, if a rope travels on and off a grooved single layer drum, it will also go through a bending cycle. Tests and practical experience have shown that that winding on a single layer drum is equivalent to bending over a sheave and will cause similar fatigue damage.

FIGURE 1. Wire rope with fatigue breaks



Usually, fatigue breaks develop in segments of the rope surface that come into direct contact with a sheave or drum. Here, various contact phenomena compound the fluctuating bending stresses. Breaks in these areas are external and usually visible. Once broken wires appear, a good many more are likely to develop within a relatively short period. Figure 1 shows a rope with surface wire fatigue breaks. Note the square ends of wires that are typical for fatigue breaks. The figure also shows abrasion-plus-fatigue patterns

characterized by chisel shaped wire ends. This is considered a long term condition normal to the operating process.

Internal breaks can develop depending on the loading and, especially, the rope construction. For example, many ropes are of the torque-balanced multi strand type comprising two or more layers of strands. Figure 2 shows a cutaway section of such a rope. Torque balance is achieved in multi strand ropes by laying outer and inner strands in opposite directions.

**FIGURE 2.
Multi strand
rope construction**



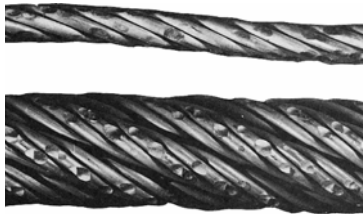
In single fall operations the use of non-rotating ropes is mandatory. This type of rope construction limits axial rotation of the freely suspended rope under load. In addition, multi strand ropes offer flexibility and a wear resistant surface profile. However, the wires and strands in different layers of these ropes touch locally and at an angle. Therefore, when multi strand ropes bend over sheaves or on a drum, they are subject to the combined effect of radial loading, relative motion between wires and bending stresses.

This causes inter strand nicking (Figure 3) and, eventually, fretting wear or fatigue across the interface between layers as illustrated by Figure 4.

Therefore, multi strand ropes are prone to develop internal broken wires. As indicated in Figure 5, this breakup occurs primarily on the interface between the outer and second layer of strands, usually with no externally visible signs. Wires in the second layer of strands typically show inter strand nicking and breaks caused by a combination of fluctuating axial wire stresses, inter-wire motions and fluctuating radial

loads. The broken wires usually have squared-off and z-shaped ends that are typical for fatigue breaks.

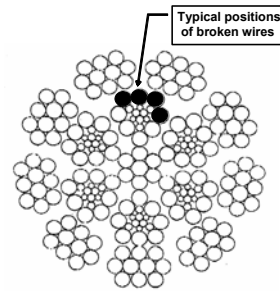
**FIGURE 3. Inter strand
nicking**



**FIGURE 4. Broken wires in
second layer of strands**

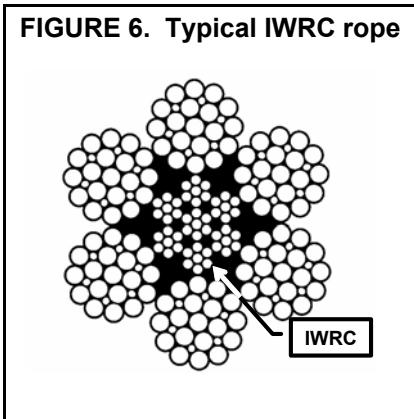


**FIGURE 5. Typical
positions of broken
wires in multi strand
ropes**



For example, on overhead traveling cranes, wire rope drums are generally single layer and spirally grooved. The rope passes over one and perhaps several sheaves. As there is no multi-layering on the drum involved, failure of the rope is usually by accumulated internal damage and fatigue rather than by wear and damage to external wires. Fatigue failure commences internally in areas where layers of the wire strands are in contact with each other. Since deterioration of non-rotating rope is not easily detected, failure of the rope is often unexpected.

FIGURE 6. Typical IWRC rope



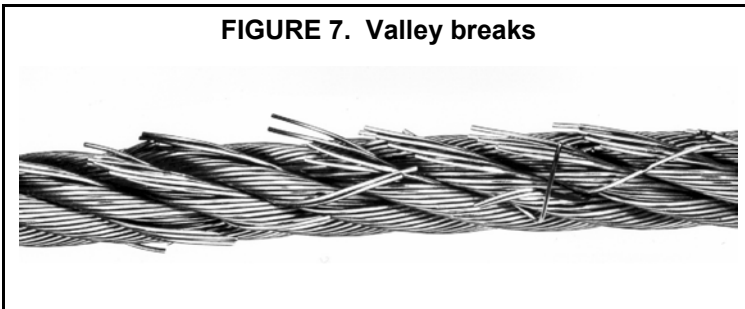
Similar nicking and fatigue patterns occur in IWRC (Independent Wire Rope Core) ropes. Figure 6 shows a typical cross-sectional diagram of such a rope.¹ For IWRC ropes, the outer wires of the outer strands have a larger diameter than the outer core strand wires. To minimize inter strand nicking between the outer strands and the IWRC, these ropes are designed such that the wires of the outer strands and the IWRC are approximately parallel. (This is usually achieved by choosing a *lang lay* construction for the IWRC and an *ordinary lay* construction for the outer strands.)

Typically, the wires of the outer strands are well supported by their neighbors while the outer wires of the IWRC are relatively unsupported.

The result of these geometrical features is that, under fluctuating tensile loads, the outer IWRC wires are continuously forced into the valleys between the outer strand wires and then released. This mechanism results in secondary bending stresses leading to large numbers of core wires with fatigue breaks. These breaks can be very close together and can form groups of breaks. Eventually, the IWRC can break, or it can even completely disintegrate into short pieces of wire about half a lay length long. This condition is commonly called *complete rope core failure*.

As the IWRC fails, the outer strands lose their radial support. This allows the wires of the outer strands to bear against each other tangentially. The resulting inter strand nicking restricts the movement of the strands within the rope. Without this freedom of movement, secondary fatigue breaks in the wires of the outer strands will develop at the strand tangent points. Because these fatigue breaks develop in the valleys between the outer strands, they are also called *valley breaks* (Figure 7).

FIGURE 7. Valley breaks



In more general terms and paradoxically, internal broken wires occur frequently in ropes that, for safety reasons, are operated with large diameter sheaves and high factors of safety. Further, when a reeving system includes sheaves lined with plastic or all plastic sheaves, these sheaves offer more elastic support than steel

sheaves. Then, the pressure between outer wires and the sheave grooves can be reduced to such an extent that, for some rope constructions, the first wire breaks will occur internally.

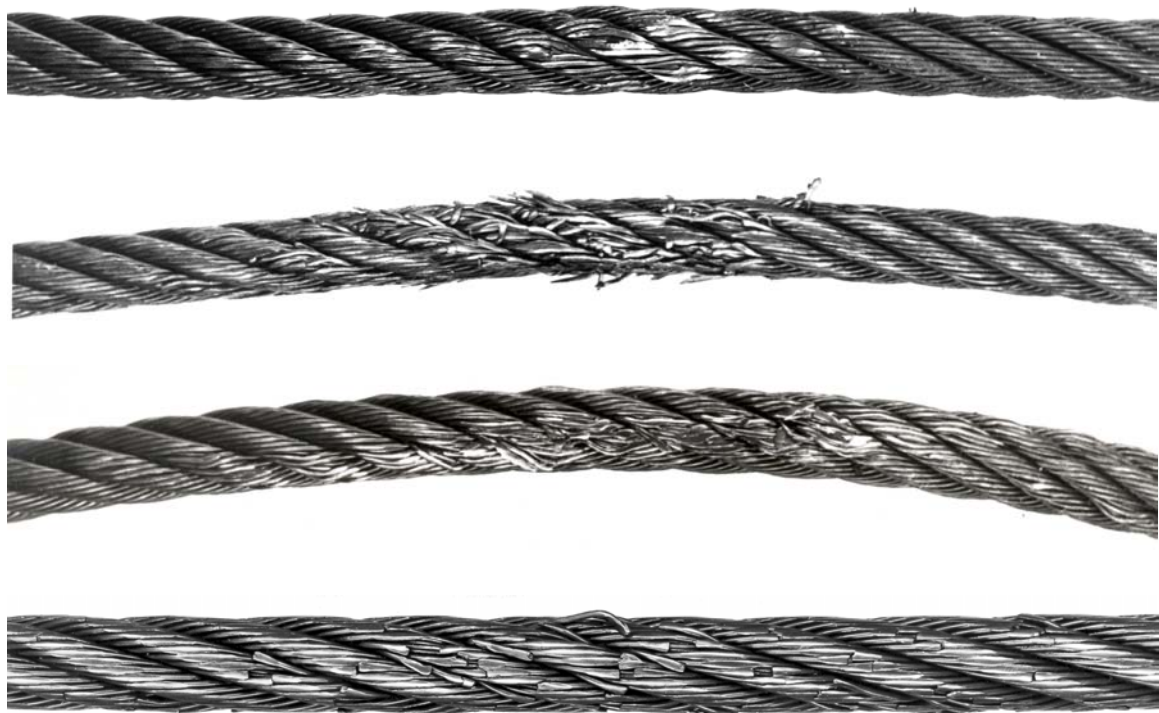
Spooling on multi layer drums²

If a rope section travels on and off a grooved multi layer drum, it goes through a bending cycle. Rope sections spooling in the first layer are bent around a smooth drum surface. When the second layer comes in, rope sections in the first layer will be spooled over, compressed and damaged on the upper side by the second rope layer. Rope sections spooling in the second and higher layers will be damaged on all sides during contact with the neighboring wraps. In addition, they will bend around the very rough surface created by the previous rope layer, leading to additional wire damage. It is obvious that by these mechanisms the rope will be damaged far more than by just one bend on a single layer drum.

The point where the rope is squeezed between the drum flange and the previous wrap, as it rises to form the next layer, is an area of accelerated wear. Typically, the slap of the rope at the crossover points can cause peening, martensitic embrittlement and/or wire plucking with the associated rope damage as the rope crosses over from layer to layer on a drum. Further, if the

lower layers were not spooled under sufficiently high tension, the lower wraps can be displaced by the incoming rope section, allowing it to slide down between them. This can lead to severe rope damage. Various types of rope damage caused by drum winding are shown in Figure 8.

FIGURE 8. Rope damage caused by multi layer drum winding



Wire rope inspection and retirement

Two different philosophies have been used to effect rope retirement:

1. A *Statutory Life Policy* mandates rope retirement at certain prescribed intervals. (This means, the *Statutory Life Policy* places a maximum on the time a rope can be in service).
2. *Retirement for Cause* is based on retirement conditions that are evaluated periodically by nondestructive inspections. (This means, the Retirement-for-Cause approach requires that the rope must be retired when the deterioration exceeds a certain limit.)

Because a Statutory Life Policy is inherently wasteful, regulators have tended to adopt the Retirement-for-Cause approach wherever appropriate.

Wire rope deteriorates gradually throughout its entire service life. To keep abreast of deterioration, wire rope must be periodically inspected. Because moderate deterioration is normally present, the mere detection of rope deterioration does not usually justify rope retirement.

The purpose of wire rope inspections is to monitor the normal process of deterioration so that the rope can be retired before it becomes dangerous. Another benefit of inspection procedures is to detect unexpected damage or corrosion.

There are two major nondestructive inspection methods for the detection and evaluation of rope degradation: Visual inspections and EM inspections.

Visual Inspection

The rag-and-visual method is a simple yet useful method for detecting a wide variety of external rope deteriorations. Using this approach, the inspector lightly grasps the rope – which moves at inspection speed – with a rag or cotton waste. External broken wires will often porcupine and, as the rope moves, snag the rag or cotton waste. The rope is then stopped at that point, and the inspector assesses the rope condition by a visual examination.

Frequently, broken wires do not porcupine. Then, a different test procedure must be used. The rope is moved two or three feet at a time and visually examined at each stop. This method is tedious and, because the rope is often covered with grease, many external and internal defects elude detection.

Another visual inspection tool is measurement of the rope diameter. Rope diameter measurements compare the original diameter – when new and subjected to a known load – with the current reading under like circumstances. A change in rope diameter indicates external and/or internal rope damage. Inevitably, many sorts of damage do not cause a change of rope diameter.

Several visible signs can indicate distributed losses of metallic cross-sectional area, due to corrosion, abrasion and wear. For example, corrosion products, flattening of outer wires and loss or, sometimes, increase of rope diameter frequently reveal external and internal corrosion. However, the extent of corrosion is often difficult to gauge and its significance is even more difficult to assess.

Visual inspections are inherently not well suited for the detection of internal rope deterioration. Therefore, they have limited value as a sole means of wire rope inspection. However, visual inspections are simple and do not require special instrumentation. When combined with the knowledge of an experienced rope examiner, visual inspection can provide a valuable supplementary tool for evaluating many forms of rope degradation.

Electromagnetic Inspections

EM wire rope inspection gives detailed insight into the condition of a rope. Its reliability has made EM testing a universally accepted method for the inspection of wire ropes in mining, for ski lifts, and many other applications.

Two distinct EM inspection methods have evolved to detect and classify defects of the LMA and LF type.

- *Localized-Flaw Inspection (LF Inspection)*. Like the rag-and-visual method, LF inspection is suited only for the detection of localized flaws, especially broken wires. Therefore, small hand-held LF instruments have been called electronic rags.
- *Loss-of-Metallic-Area Inspection (LMA Inspection)* detects and measures changes of the metallic cross-sectional area caused by wear and corrosion. More reliable than visual diameter checks, LMA inspection can replace diameter measurements made with a caliper. Therefore, LMA instruments could be called electronic calipers.

Electromagnetic and visual wire rope inspections complement each other. Both are essential for safe rope operation, and both methods should therefore be used for maximum safety. The thrust of evolving regulations is clearly toward combined periodic EM and visual inspections

A thorough inspection must consider all aspects of a rope's condition, including:

1. the findings of a visual inspection,
2. the results of an EM rope inspection,
3. the rope's operating conditions and related damage mechanisms,
4. the history of the rope under test and that of its predecessors.

A program of periodic inspections is especially effective. To establish baseline data for subsequent inspections, such a program should commence with an initial inspection of the installed rope after a certain break-in period. Subsequent inspections should then be performed at scheduled intervals. In particular, periodic EM inspections allow the documentation of a rope's deterioration over its entire service life.

Inspection of ropes that develop internal broken wires, especially non-rotating multi strand ropes

Under normal operating conditions, *multi strand ropes that wind on a single layer drum* pose a particularly difficult inspection problem. As pointed out previously, this type of rope usually fails from fatigue. Inter wire nicking and fatigue breaks occur internally, usually at the interface between the outer and second layer of strands. Fatigue breaks of wires occur without any visible indications, which makes visual inspections ineffective.

Since visual inspections are ineffective, a *statutory life* policy for rope retirement is usually adopted for multi strand ropes. This means that wire ropes are often discarded long before the end of their useful service life, and, literally, tens of millions dollars' worth of expensive and perfectly good wire rope is discarded annually. At the same time, this wasteful and overcautious approach by no means assures wire rope safety.

Following some slightly twisty reasoning, it has even been suggested that non-rotating rope should not be used if cranes use single layer winding on a drum. According to this way of thinking, multi strand ropes should be used only when winding on multilayer drums. Then, broken wires on the surface of the rope caused by wear, scrubbing or pulling in from one layer to the next begin to develop. As this damage is visible and progresses faster than the accumulation of internal wire damage, these non-rotating ropes are usually replaced because of external damage, long before they can fail due to internal fatigue.³

In cases where internal broken wires are a problem, electromagnetic rope testing can offer a solution. There are, however, some details that must be considered.

Regulations usually require rope retirement when the number of broken wires per unit of rope length (e.g., lay length or 10 times rope diameter) exceeds certain limits.

The discard numbers of wire breaks specified in retirement standards refer solely to external wire breaks. Appraising the condition of a wire rope with internal breaks is therefore left to the inspector. It would behoove him to discard a wire rope when the maximum total number of external and internal wire breaks per unit of rope length reaches the discard number specified in the standards.

On the other hand, the detailed detection and quantitative characterization of internal broken wires in ropes with many breaks and clusters of breaks pose problems. Difficulties are caused by the fact that, for electromagnetic wire rope inspections, the indication of a broken wire is influenced by a number of parameters like

- a) broken wire cross-sectional area,
- b) broken wire gap width, and
- c) the position of the broken wire within the cross-section of the rope.
- d) For clusters of broken wires, an additional problem is caused by the fact that the relative position of broken wires with respect to each other along the length of the rope is not known. For example, the gaps of broken wires could be aligned or staggered.
- e) Finally and most importantly, broken wires with zero or tight gap widths are not detectable by electromagnetic inspections because they do not produce a sufficient magnetic leakage flux.

Considering the above, only an estimate of the number of broken wires is possible.

Conventionally, the LF trace is used for the detection of broken wires. However, the LF signal is not quantitative and cannot be used for estimating the number of internal broken wires per unit of rope length.

Conversely, if many internal broken wires are present, the LMA trace will show rapid relatively small variations of cross-section. These variations are significant and can be used to estimate the number of broken wires per unit of rope length. Note, however, that the *averaging length* or *quantitative resolution* of the instrumentation used must be sufficient to allow this *quantitative defect characterization*. Round robin tests have shown that only very few rope testers offer the superior performance and sufficient LMA resolution required for solving this rather difficult defect characterization problem. Most rope testers failed at this problem, some of them miserably.⁴

Example 1. Experimental multi strand rope inspection⁴

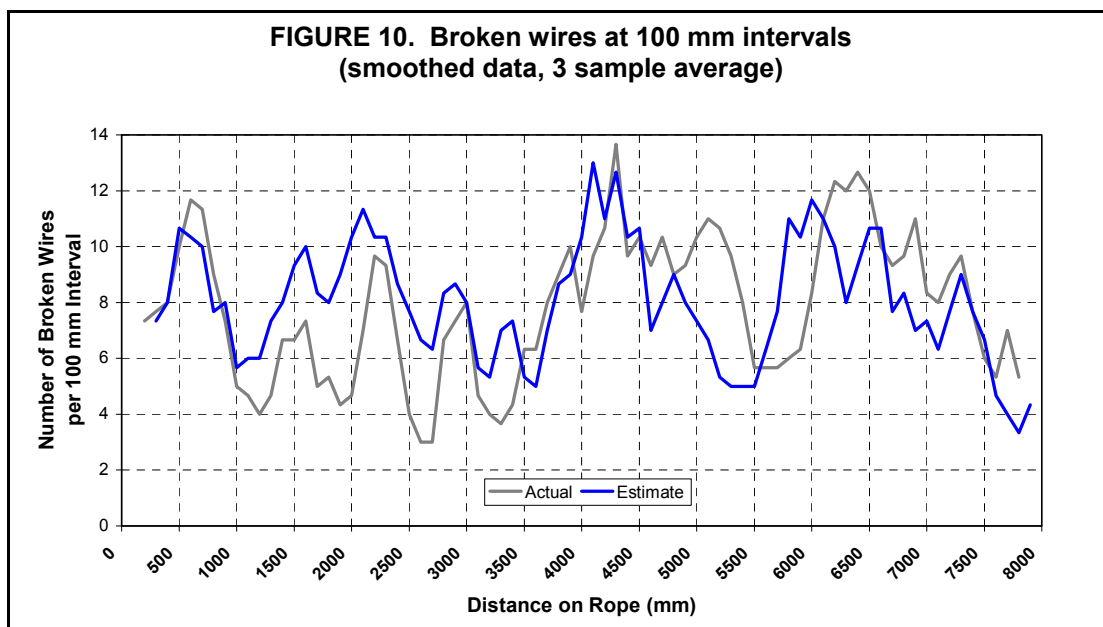
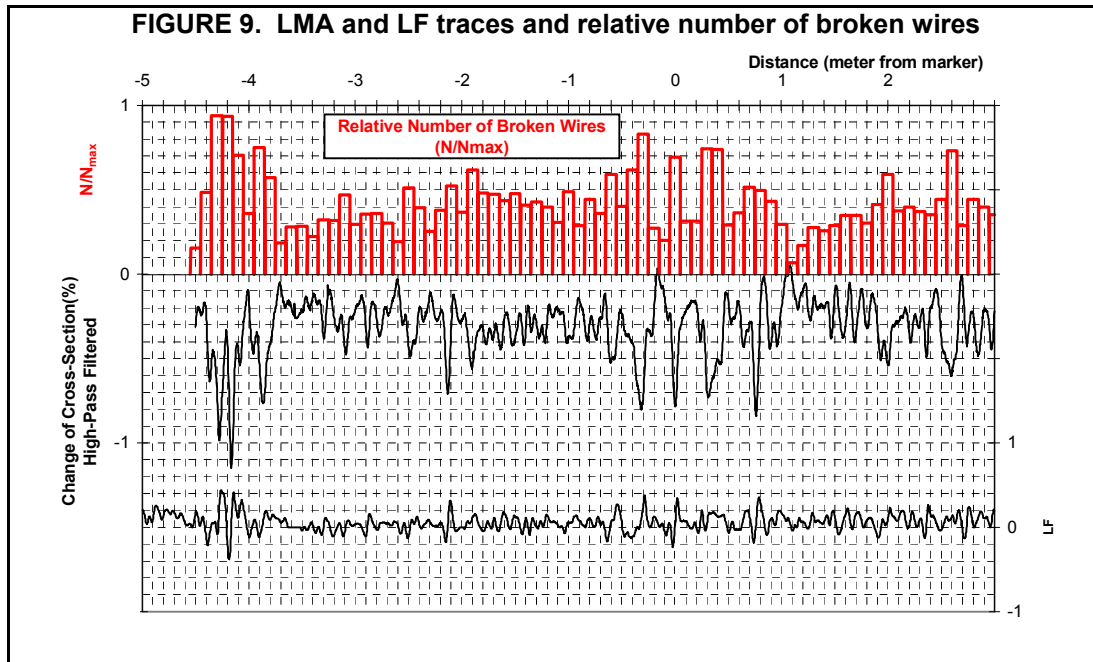
This experimental inspection, performed with an LMA-175 rope tester from NDT Technologies, Inc., illustrates the use of EM wire rope inspections for the detection and quantitative characterization of internal broken wires and clusters of broken wires. The present experiment deals with the inspection of a torque balanced multi strand rope with no corrosion and many broken wires. This rope has been used as a mine hoist rope on a trial basis and was known to contain numerous internal broken wires along its entire length. The present experiment has particular value because the rope was disassembled after the inspection, which allows a correlation between the estimate and the actual number of broken wires.

The task at hand was to determine the number of broken wires in 100 mm segments along the length the rope. The difficulty of this quantitative defect characterization problem was compounded by the fact that an undamaged rope section – usually the segment directly above the conveyance – was not available for comparison. Further, at the time, the correlation of the typical deterioration modes of this and similar ropes with their EM inspection results was generally not well understood.

A cross-sectional diagram of this multi strand rope is shown in Figure 5. As indicated in the figure, it is known that broken wires in multi strand ropes usually develop in the second layer at the interface between the first and the second layer of strands. In addition, from this and similar ropes' service histories, it can be assumed that the rope under inspection has developed significant inter strand nicking together with numerous fatigue breaks of wires in the second layer of strands.

The estimated number of broken wires per 100 mm of rope length, N , derived from the LMA trace, is shown on the top of Chart 9. Here, N_{\max} denotes the maximum number of broken wires per 100 mm of rope length. Based on the operating history of this and similar ropes, a value of $N_{\max} = 20$ can be estimated.

The rope was subsequently disassembled to determine the actual number of broken wires per unit of rope length. Broken wire estimates together with the actual number of broken wires along the length of the rope are shown in Figure 10. Considering the fact that the LMA trace not only indicates broken wires but also inter strand nicking, internal wear and other disturbances of the rope structure, there is a good correlation between the actual and estimated number of internal broken wires. The correlation between actual and estimated number of broken wires up to a rope distance of about 4500 mm is very good. Beyond this distance, there is an offset, which is probably due to a distance measurement error during disassembly of the rope.



A destructive break test of the rope showed a 30.2% loss of breaking strength. On the other hand, the second layer of strands of the rope (see Figure 5) represents about 30% of the total rope cross-sectional area. This leads to the hypothesis that, for this rope, the second layer of strands has lost all load-bearing capability.

The lack of sufficient information on the rope's operating history – and that of its predecessors – made this rope evaluation particularly difficult. Under normal circumstances, these details are known and must be considered when assessing the rope condition. Altogether, this evaluation shows that a quantitative defect characterization for ropes with internal broken wires and clusters of broken wires is possible. The example illustrates the capabilities and limitations of EM wire rope inspection methods for this particular defect characterization problem.

Note, however, that data interpretation can become routine as soon as the correlation between test results and the actual rope condition has been established for different rope categories.

Example 2. Inspection of IWRC (Independent Wire Rope Core) wire rope

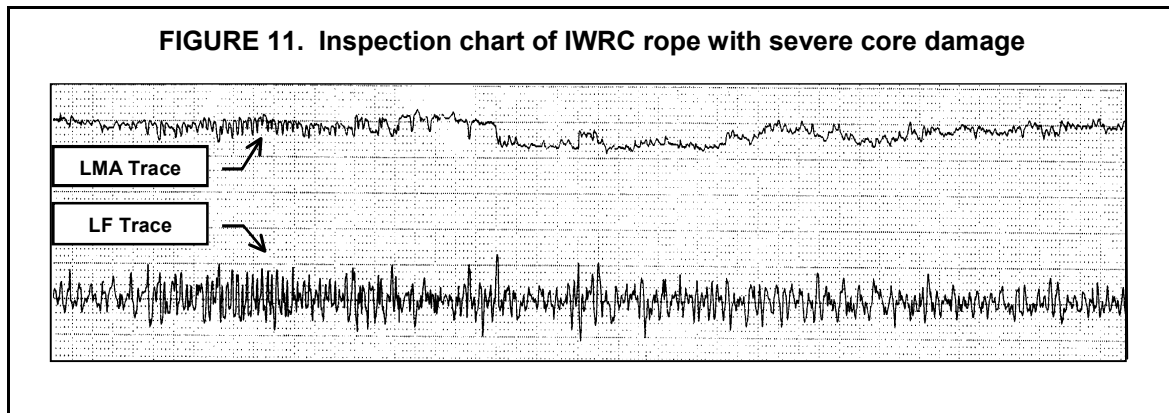


Figure 11 shows the results of an IWRC rope inspection (Figure 6). The chart recording indicates a severe breakup of the independent wire rope core. As previously discussed, this is strong evidence of heavy fluctuating tensile fatigue loading. Note that the LMA and LF traces show the typical patterns of broken and missing wires. The *missing wire* patterns even indicate that short pieces of broken IWRC wires might have fallen out of the rope. In addition, together with the findings of a visual inspection, the chart together with a visual inspection indicates severe corrosion, including corrosion pitting.

Inspection of ropes that spool on multi layer drums

As discussed above, winding-on-drum damage is usually external and can be detected by visual inspections. However, in spite of their conceptual simplicity, visual inspections are by no means easy and require a well qualified and experienced inspector.

Under all conditions, an electromagnetic inspection will greatly enhance the accuracy and reliability of inspections. In addition, dependable inspection procedures, using combined visual and EM methods, can detect rope deterioration at its earliest stages. Therefore, wire rope users can employ them as an effective preventive maintenance tool. To illustrate, here are some practical examples.

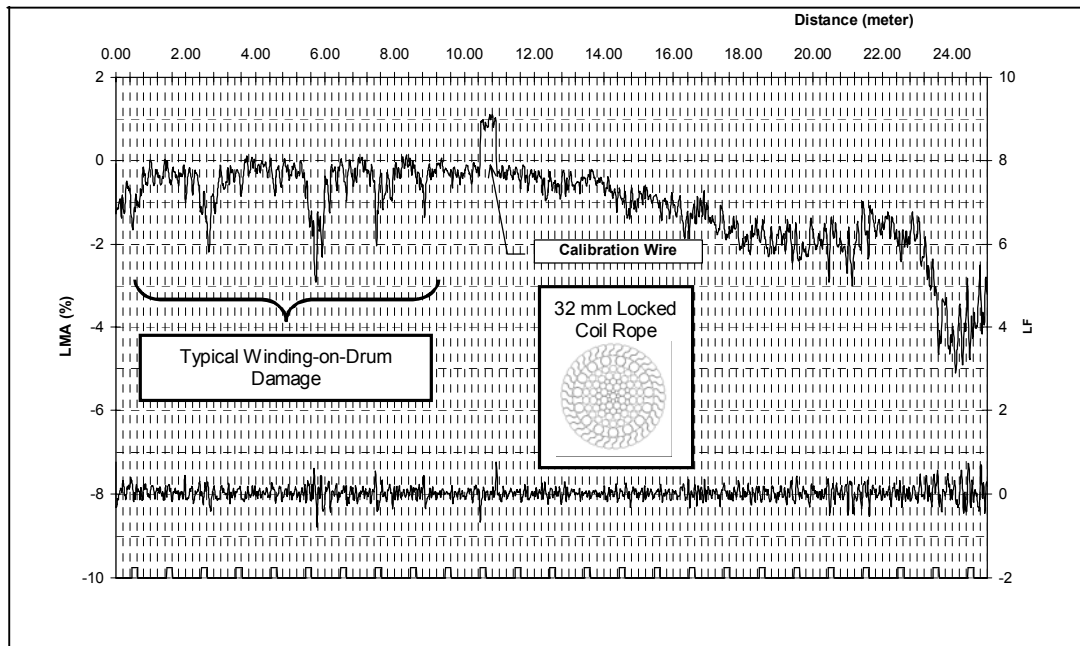
1. The early detection of corrosion allows immediate corrective action through improved lubrication.
2. Accelerating wear and inter strand nicking can indicate a need to reline sheaves to stop further degradation.
3. Careful inspections can monitor the development of local damage at the crossover points of the rope on a winch drum. This way, the operator can determine the optimum time for repositioning the rope on the drum.

Example 3. Winch rope inspection⁵

This locked coil rope was mounted on a mobile winch for approximately 10 years after 3 months earlier use on a friction winder installation. Its cross-sectional diagram is shown as part of Figure 12. The rope showed clear evidence of external corrosion, variable along the test length. Using retirement criteria that are appropriate for visual inspections, this rope would have been rejected for further use. Due to its service history the rope was not believed to contain any internal local defects.

Examination after dismantling. After dismantling, the rope showed severe corrosion on the outer layer and also significant corrosion on the second layer. The third layer showed less corrosion, and from the fourth layer onward the rope appeared undamaged, because lubricants were still present. No local defects were found.

FIGURE 12. Chart of winch rope inspection



Findings of electromagnetic inspection. Figure 12 shows an EM inspection chart of this rope. The maximum measured LMA is 5.1% compared to the best section on the rope covered by the chart. Note that the most convenient calibration method for EM inspections is to attach a calibration wire with known cross-sectional area to the rope. In the present case a wire bundle that represents about a 1% increase in rope cross-section was taped to the rope and used for calibration. This is indicated in the chart of Figure 11.

The chart shows variable corrosion, corrosion pitting and, possibly, broken wires. As discussed previously, the slap of the rope at the crossover points can cause peening, martensitic embrittlement and/or wire plucking with the associated rope damage as the rope crosses over from layer to layer on a drum. The deterioration pattern indicated to the left of the chart is typical for ropes that wind on a drum with the worst deterioration occurring at the crossover points as the rope slips from layer to layer while winding on a multilayer drum.

Example 6. Diving bell rope inspection

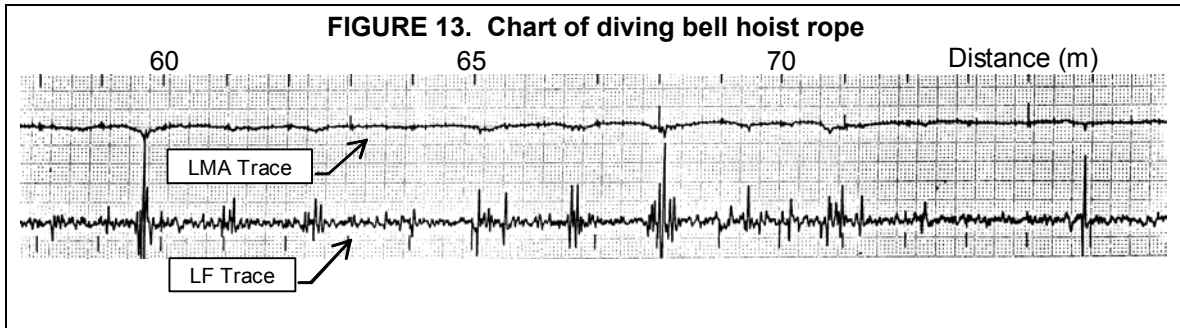


Figure 13 shows an EM inspection chart recording of a 30 mm die-formed multistrand diving bell hoist rope. When using non-rotating diving bell ropes, there are normally several layers of rope on the drum. The slap of the rope as it crosses over from layer to layer on the drum can cause peening, martensitic embrittlement and/or wire plucking with the associated damage.

This rope shows periodic groups of broken wires at these cross-over points. This damage is visible. Usually, the external deterioration progresses faster than the internal wire fatigue damage that is typical for multi strand ropes. Therefore, many non-rotating ropes that are wound on drums are replaced because of external damage, long before they will fail due to internal wire fatigue. However, the possibility of internal fatigue damage should always be considered for these ropes.

The maximum LMA for the rope under test is 1%. The rope section shown is subjected to the full in-air weight as the bell is lowered and raised. On the basis of the EM inspection, a decision was made to cut and re-terminate the rope behind the first defect about 58 m from the diving bell.

Summary and Conclusion

Combined with visual inspections, electromagnetic inspections can greatly increase the accuracy and reliability of crane rope examinations. This is especially true for ropes that develop internal broken wires such as torque balanced multi strand ropes and IWRC ropes. Combined visual and EM inspections can also be used as a powerful preventative maintenance tool. Altogether, the use of EM inspections promises improved crane safety. In addition, EM inspections are an effective preventative maintenance tool that promises considerable cost savings.

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