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Magnetic Field Techniques for the Inspection of Steel Under Concrete Cover

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Abstract:

The results of a study comparing residual magnetic field measurements to magnetic flux leakage measurements as methods to detect broken prestressing steel are presented. Analysis of two and three dimensional magnetic field plots shows that the residual magnetic field technique has strong potential in this application, with detectable signals from a single broken wire on a seven strand cable being found up to 70 mm from the cable surface. Magnetic flux leakage measurements with the same yoke produced detectable signals only when the cable was completely severed, indicating that the yoke was not driving the cable into saturation during the magnetisation process. However, the residual field technique was also found to be very sensitive to the technique used to magnetise the object being inspected, indicating that considerable care would be necessary to use the technique successfully in the field.

Keywords

magnetic methods, magnetic materials, concrete, ferritic steel, infrastructure

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Introduction:

The inspection of pre-stressing and other steel under concrete cover is a particularly difficult non-destructive evaluation (NDE) problem. Concrete is strong in compression but not in tension. In pre- and post-tensioned structures the concrete is kept in compression by applying tension to steel reinforcements inside the concrete. The applied compression enables the concrete to support higher loads than those experienced by a simple reinforced concrete structure. In either case the strength of the concrete structure depends on the integrity of the steel inside it and failure of the steel reinforcement, typically due to corrosion, leads to failure of the structure.

It is often very difficult to detect damage to reinforcing steel using conventional NDE methods. The concrete cover prevents visual inspections of the reinforcing steel and makes ultrasonic inspection difficult due to the porous, non-uniform nature of the mortar and aggregate that compose it. X-ray inspections are often difficult, dangerous or impossible to perform due to the geometry and location of the structures that need to be inspected. However, a variety of novel inspection techniques have been developed to address this problem. These techniques have relied on four basic approaches:

- looking for damage to the concrete that indicates problems with the steel reinforcement;
- looking for evidence of corrosion activity;
- detecting the actual moment of failures in pre-stressing steel; and
- directly detecting areas of damaged steel.

Examples of the first approach include impact echo[1] and spectral analysis of surface waves[2] techniques that determine the condition of the concrete itself and ground penetrating radar[3] techniques that look for evidence of concrete delaminations produced by corrosion in the pre-

stressing steel. This approach has the disadvantage of only giving information on the condition of the concrete itself, rather than the steel inside the concrete. In the second category, typical corrosion monitoring techniques such as half-cell potential[4] measurements will generally indicate only that corrosion activity is occurring instead of showing the extent of the damage to the steel inside the concrete. The third category represents a more recent approach for pre- and post-tensioned concrete structures where acoustic emission monitoring is used to detect the sound of the reinforcing wires breaking in buildings[5], bridges[6] and pre-stressed concrete cylinder pipe[7]. This approach directly detects wire failures but will only indicate the damage that takes place during the monitoring period. The fourth category includes two very recent developments – the use of the remote field effect to detect breaks in pre-stressing wires in pre-stressed concrete cylinder pipes[8] and the use of residual D.C. magnetic flux measurement techniques to find broken prestressing steel in general[9] and more specifically in building beams[10] and bridges[11]. In the latter type of technique the pre-stressing steel is magnetised using a permanent magnet yoke passing along the length of metal to be inspected. After the yoke has been removed residual magnetic fields produced by the remnant magnetisation of the steel object are measured. Damage to the metal is detected as an increase in the measured magnetic fields. The concrete cover over the steel prevents direct contact between the yoke and the steel, so the magnetisation of the steel is much less than would be the case if direct contact was possible. However, the literature reports that the detection of residual magnetic fields at wire breaks and other areas of damage is still possible once the magnetising yoke has been removed from the area of inspection.

The work on residual magnetic flux leakage is of particular interest both because it provides a technique to directly inspect pre-stressing steel that previously could not be examined

and because there is a considerable body of information on the use of magnetic flux leakage techniques to detect damage in pipelines[12-15] and in wire ropes[16-17]. The technique used during magnetic flux leakage inspection is similar to that described above for the residual flux measurements. However, there is direct contact between the magnetising yoke and the steel during a magnetic flux leakage inspection. In addition, the measurement of the leakage flux around damage to the pipeline or wire rope is made while the object being inspected is actively being magnetised by the yoke, rather than after the yoke has been removed. Magnetic flux leakage has also been reported as a technique to detect prestressing steel failures in bridges[18]. Many of the reported results in the literature on the residual magnetic flux measurement technique contradict the previous experience with magnetic flux leakage. Features of the reported residual flux measurements include a need for multiple magnetising passes before a measurement is made[9], no requirement for contact between the magnetising assembly and the metal object being inspected[9,10], and a sensitivity to thin cracks[10]. In contrast, magnetic flux leakage measurements are made during a single magnetising pass, generally require contact between the magnetising assembly and the object being inspected, and are much more sensitive to corrosion pits than thin cracks[12]. The differences between the two techniques led to the work reported in this paper, which was done to directly compare their usefulness for the detection of damage in steel under concrete cover. A series of comparisons were made between residual flux measurements and magnetic flux leakage measurements using seven strand prestressing cables that had single and multiple wires damaged using both saw cuts and a corrosion cell. The latter approach duplicated the most common damage seen in pre-stressing cables, where a single wire strand breaks in one location followed by additional breaks in the other strands in the cable at other locations until the entire cable has been severed. NDE techniques

therefore need to be able to detect the failure of a single strand for this application, rather than the entire cable.

Experiment:

Figure 1 shows a schematic diagram of the apparatus used in the magnetic flux leakage experiments. This particular arrangement duplicates a possible approach to magnetising prestressing cables in concrete beams which allows cables adjacent to the one being inspected to be used as the return path for the magnetic flux to complete the magnetic circuit. Preliminary experiments had shown that the field produced by the yoke would interfere with the measurements if a simpler arrangement with the cable placed directly across the two legs of the magnetising yoke was used. The arrangement shown in the figure prevents such interference and allows the relatively heavy yoke to be kept stationary while a much lighter sensor array is moved across the cable. The D.C. magnetic field in the circuit was provided by eight 12 mm thick NdFeB rare earth magnets. While this circuit magnetises the cables, it will not provide enough energy to drive them close to magnetic saturation, which is the desired operating point for magnetic flux leakage circuits. A larger number of magnets would be required to provide the energy necessary to magnetise a real pair of pre-stressing cables, which are typically between 20 and 25 m in length. Measurements were made with the cables directly in contact with the two yokes to provide the best possible case results. These measurements were then followed by measurements made with the cables separated from the two yokes by a distance of 2 cm, which is the smallest amount of concrete cover found in the beams made with this type of pre-stressing steel.

The smaller, U shaped yoke portion of the circuit was also used to magnetise the cables prior to residual magnetic flux measurements being made. Figure 2 shows the two different

magnetising procedures that were used to create the residual magnetic flux. In both cases the cable was pulled along the top of the yoke (steps 1 and 2) until its end was reached (step 3). For most of the data reported here the cable was then pulled directly away from the yoke while both ends of the yoke touched the cable (step 4a). In other cases the cable continued to be pulled over the yoke until it was no longer in contact with any part of it (step 4b). The first case simulated what would happen when a magnetising assembly reached the end of an installed cable while the second simulated the results that would be expected in the centre of an installed cable. In most cases the magnetisation was done with the yoke directly in contact with the cable in order to maximise the residual magnetic field in the cable. However, a set of measurements was also performed using the second magnetising procedure but with the cable 2 cm above the yoke in order to simulate the effects of the concrete cover on the measurement procedure. This reduced the strength of the measured signal but did not otherwise change it, indicating that a stronger magnet may be able to compensate for the concrete cover during the magnetising stage of the inspection.

The fields around the cable were measured in the plane of the radius of the cable by three Hall probes mounted on an arm that was moved by a computer controlled, precision X-Y positioning device (accurate to 0.01 mm). The Hall probes were arranged orthogonally so that axial, circumferential and radial components of the magnetic field could be measured. Figure 3 shows a close up of a notched cable. It indicates the plane in which measurements were made, the field directions in that plane and the location of the spatial axes used in the subsequent figures. The Hall probe signals were amplified and filtered using analog circuitry and then measured by a voltmeter connected to a computer, which recorded their value, which had an

uncertainty of ± 0.02 mT. The computer also controlled the operation of the voltmeter and the position of the Hall probes.

The prestressing steel cables in the experiments were composed of seven wire strands, with a central core of a single wire and the remaining wires wrapping around the core. The diameter of the cable was 16.5 mm and each wire had a diameter of 5.5 mm. Initial measurements were made on cables with approximately 20 mm long sections removed from a single wire using a specially designed corrosion cell that confined the damage to the wire to the desired area. The area removed is referred to as a “notch” in the remainder of this paper. Past experience with notches and other defects produced by mechanical methods such as sawing has shown that the resulting residual stresses can cause spurious defect signals due to changes in the sample permeability. Using a corrosion cell to produce the notches prevented these spurious signals and ensured that the changes observed in magnetic behaviour were due to the notches themselves.

Most of the residual flux and magnetic flux leakage experiments were made with the Hall probe positioned on the side of the cable with the notch. This arrangement was expected to produce the strongest magnetic signal. However, there is no reason to believe that such an orientation would be more common in the field than ones with the defect located at 60° , 120° or 180° around the cable from the side closest to a magnetic inspection tool. Measurements were therefore also done to investigate the effect of that rotation on the magnetic field strength.

Although the first magnetic flux leakage measurements were made using a notch cut in a single cable, no magnetic flux leakage field was detected. Subsequently, additional cables were severed using a saw until the entire cable had been cut. Flux leakage measurements were then made after each additional increase in the number of severed cables. The problems associated

with residual stresses were not considered to be as important in this case as the measurements were made to determine if any signal could be detected, rather than to reproduce the signals that might be expected in the field.

Results:

Figure 4 shows three dimensional field maps of typical residual flux patterns measured during the experiment, with Figure 4a showing the axial component of the field when the notch is not rotated away from the Hall probe and Figure 4b the radial component. The circumferential component is not shown as it falls off very rapidly away from the cable and no measurable signal could be detected at 20 mm from the cable surface. The double peak in the axial results near the cable can also be seen in Figure 5, which plots the values of the axial, circumferential and radial field components measured at 2 mm away from the cable surface. The circumferential results have been offset by -2 mT and the radial results be $+2$ mT for clarity on the diagram. The solid lines in this Figure give the approximate boundaries of the notch. The corrosion cell process does not produce a linear interface in the same way as a saw cut, so a precise notch edge is impossible to define.

Figures 6a and 6b show similar linear plots of the axial and radial components of the residual magnetic field, but with measurements made at 20 and 50 mm from the cable surface. The 20 mm results include data from measurements made with the notch rotated at both 0° and 180° from the Hall probe array. The results for the other measured angles of rotation (60° , 120° , 240° and 300°) fall between the two extremes. Note that even when the cable is rotated 180° from the Hall probe a signal can still be seen from the notch in both field components. Only the 0° degree measurements at 50 mm from the cable are shown in the figures. The results for the other orientations show the same behaviour within the uncertainty of the measurements. No

discernable signal from the notch can be seen in the axial measurements, but a change in slope occurs in the radial field values in the region of the notch, indicating that detection of wire damage may still be possible with this amount of concrete cover.

Figures 7 to 9 illustrate the effects of variations in the magnetising procedures on the results. Figure 7 shows the changes in the radial field component measured at 20 mm due to multiple passes of the cable over the magnetic yoke. Note the similarity of the results to each other and the lack of a consistent trend in their behaviour as the number of passes increases. Figures 8a and 8b show three dimensional plots of the residual magnetic field produced when the cable is magnetised using the procedure shown in Figure 2, stage 4b. This procedure produces significantly stronger signals than those produced by the stage 4a procedure. Figures 9a to 9c show the axial, circumferential and radial field components respectively as measured at 2, 20 and (for Figures 8a and 8b) 50 mm from the cable surface. While the circumferential signal already disappears at a distance of 20 mm from the cable, the axial and radial components show clear signals at 50 mm from the cable. In this case the axial field increases by 0.15 mT from the edge of the measured region to the centre of the notch, while the radial field experiences an equal change in its value as it crosses the notch.

Finally, Figure 10 compares the axial flux leakage results produced by six severed wires with 20 mm notches to those produced from a completely severed cable with a 20 mm spacing between cable ends. The results from one to five severed wires are not shown as no discernable signal can be detected at 20 mm from the cable. As shown, only the completely severed cable produces a noticeable signal at this spacing. However, the signal measured at 2 mm from the severed cable is the largest of any recorded during the experiment. This is not surprising, as the measurements were made when the cable was in direct contact with the magnetic yoke. The

experimental setup therefore approximates that of a magnetic flux leakage tool used for wire rope inspection, a common commercial application of magnetic flux leakage technology. Note the differences between the severed cable's axial field component next to the cable and that of the residual field in Figure 8a, including a reversal in the change of field direction and the lack of the double peak in the field. The radial component shows a similar reversal in field direction between the two types of measurements, while the circumferential equivalent to Figure 10 shows a field variation similar in appearance to the radial component, rather than the double peaks shown in Figure 8b.

Discussion:

Residual Flux Measurements:

It is apparent from the results in Figures 4 and 8 that magnetising a broken wire on a prestressing cable produces a clear residual flux field in the region of the wire break. These signals are readily detectable, with the radial component approaching a peak to peak value of 8 mT at 2 mm from the cable in Figures 8 and 9. However, the inspection of pre-stressing cables under concrete requires measurements at a greater distance from the cable surface than 2 mm. Typical concrete cover values range from 20 mm to 90 mm or more and may vary significantly across the length of a single cable. The utility of any inspection technique will therefore depend on both its ability to produce measurable signals at an appropriate distance from the prestressing cable and on its ability to compensate for changes in the cable position during the inspection. Examining the results of Figures 4 to 9 shows that residual flux fields can readily be detected at 20 mm from the cable. Detection of residual flux fields can also be achieved at greater distances, but the results appear to be partly dependent on the magnetisation technique used to produce the residual field. Defects under concrete cover will therefore be more difficult to detect at the ends of a cable than in its centre. This result also suggests that more care would be required when

inspecting cables under thicker amounts of concrete cover to make sure that the magnetising yoke runs directly along the cable, duplicating the stage 4b procedure in Figure 2, rather than drifting off to one side of the cable, which would more closely approximate the stage 4a procedure.

The measurements shown in Figure 8 indicate that measurable changes in the magnetic field around the cable due to a single wire break can be detected in the laboratory as much as 70 mm from the cable. Beyond that point the magnitude of residual flux signal begins to approximate the uncertainty of the measurements due to background magnetic flux variations and it is difficult to discern a usable signal. However, these measurements do not necessarily mean that the residual flux leakage measurements can be made on cable with a maximum concrete cover of 70 mm. There are two factors that would act to change the maximum concrete cover allowable for the technique in the field. The first is that it is clear from the magnetic flux leakage measurements made during the experiment that the magnetic yoke did not saturate the cable. This point is discussed in more detail below. Fully saturating the sample during the magnetisation process before making a residual flux measurement should be expected to produce a stronger residual magnetic field than was observed here and should therefore allow the detection of broken wires under greater depths of concrete cover than the maximum value of 70 mm indicated here. This increase in acceptable concrete cover is mitigated by the fact that the cable in these experiments was magnetised using direct contact between the yoke and the cable in order to produce a stronger residual field. Such a procedure would not be possible in the field, where the yoke would have to be separated from the cable by the concrete. Further experiments or magnetic modelling will be necessary to determine whether a stronger magnetic yoke can

successfully compensate for the effects of the concrete cover and to find the maximum thickness beyond which a wire break will not be detected.

It should be noted that the capability of detecting signals from single broken wires at a given distance from the cable in the laboratory does not mean that such a level of detection would necessarily be possible in the field. As with any inspection technique, problems with background noise and poor operating conditions will lower the sensitivity of this type of measurement. In addition, the measurements shown in Figure 7 show that the magnetising technique itself will affect the results. This figure shows variations in the measured flux that depend on the number of magnetising passes the cable has experienced. No discernable trend is seen in the measurements with an increasing number of magnetising passes. The lack of such a trend and the similarity of the plotted curves suggests that the variation in results shown here is due to minor differences in the magnetising procedure, rather a change in the degree of saturation of the cable with an increasing number of magnetic passes. This sensitivity to magnetising technique means that the technique's ability to detect single broken wires is likely to be considerably reduced in the field as compared to the laboratory due to the lower control of the magnetising process that must be expected under field conditions.

Comparisons to Magnetic Flux Leakage Measurements:

Magnetic flux leakage (MFL) is already well known as a technique used inspect wire ropes[16-17]. The intention of examining MFL in this series of experiments was therefore not to duplicate past work, which has shown that single wire breaks in bundles of a large number of wires may be detected, but to directly compare the signals produced by the same yoke when operated in both a residual magnetic field and a MFL mode.

The results of Figure 10 show that the yoke arrangement used in the experiment will not produce a large MFL signal unless the cable has been completely severed. Once the cable has been cut, the signal is larger than that measured using the residual technique, but even with 6 of 7 wires cut no flux leakage signal can be detected. A comparison between the results shown in Figure 9a and Figure 10 clearly indicates that the residual flux measurement method is superior for the detection of cable damage when the cable can not be driven into magnetic saturation. The residual flux method can detect single wire breaks at a distance of up to 70 mm from the cable using this particular yoke, while the MFL method can not detect any signals due to the cutting of up to six wires.

The reasons for this difference in signal strength are likely due to a fundamental property of magnetic flux lines. During a MFL inspection the magnetic flux travels from the yoke into the object being inspected and back into the yoke again to form a closed loop. Low levels of magnetisation in the inspected object from this type of system have been identified as a major cause of poor signal amplitude in magnetic flux leakage inspections[14]. The flux takes a minimum energy path in completing the closed loop. If the object being inspected is not close to saturation, no field will “leak” from any defects present as the flux lines will instead be able to travel within the surrounding metal. Saturating the sample forces the flux lines to enter the air above the defect, allowing the leakage fields to be detected.

In the case of the residual field approach, the residual fields are being measured not while the cable is being magnetised, but after magnetisation has taken place. The passing of the yoke along the cable surface will have exposed the cable to magnetic fields oriented in several different directions as the yoke moved across it. The observed magnetic field is then due to the magnetic poles left at the surface of the cable by the applied magnetic field. The double peak in

the axial field in Figures 4a, 5 and 9 suggests that the actual flux distribution produced by this magnetisation process is different from the simple “across the defect” flux distribution typical of MFL results, which would generally be expected to have the axial field behaviour shown in Figure 10. Magnetic modelling or further experimental work would be necessary to develop an accurate understanding of the real field distribution.

Conclusions:

The results presented here confirm the potential of the residual flux measurement method as a technique for inspecting pre- and post-stressing steel under concrete cover. Depending on the method used to magnetise the steel, a measurable change in the magnetic field around the cable due to the severing of a single wire could be detected as much as 70 mm from the cable surface. The rotational orientation of the notch to the location of the field measuring sensor affects the strength of the result, but does not prevent the location of cable damage. While the cables were magnetised in direct contact with the yoke for most of the measurements reported here, additional measurements made with the magnetising yoke separated by 20 mm from the cable also showed that magnetising through concrete cover is possible. The residual flux technique is also clearly superior to magnetic flux leakage as a technique to detect wire break under concrete cover, being able to detect a single wire break where MFL will only produce a signal from a completely severed cable.

However, the results also showed that the residual flux leakage technique is very sensitive to the way in which the cable has been magnetised. Measurements made after multiple magnetising passes along the same cable showed that only a single magnetising pass is necessary to produce the maximum level of magnetisation from a yoke. Small variations in the magnetising technique produced different signal levels and shapes, suggesting that interpretation

of the signal in the field may be difficult. Major variations in the magnetising technique, such as those that would occur between the cases in which the cable is magnetised near an end or in its centre, produce equally large variations in the signal. Care would be necessary to determine the best magnetising technique for any given application and to ensure that technique was used during an inspection. This sensitivity to the magnetising technique, in addition to the inherent difficulties in transferring laboratory research to field means that the sensitivity of the technique to broken wires is likely to be significantly lower in the field than that reported here.

Further experimental research is required to determine the effect of stress on the residual field measurements, the actual shape of the residual flux fields and the maximum depth of concrete cover that will permit a successful inspection. Determining the best design for a field magnetising system and tests on laboratory models of concrete beams and in the field will complete the development of the technique.

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References:

1. Sack, D. and Olson, L. 1994, In-situ Nondestructive Testing of Buried Precast Concrete Pipe, Proceedings of the American Society of Civil Engineers 1994 Materials Engineering Conference, San Diego, November 13-16, 1994, American Society of Civil Engineers, New York.
2. Krstulovic Opara, N., Woods, R.D., Al Shayea, N., Nondestructive testing of concrete structures using the Rayleigh wave dispersion method, American Concrete Institute Materials Journal, Vol. 93, no. 1, pp. 75-86, 1996.
3. Bungey, J., 1995, Testing concrete by radar, Concrete, November/December, Concrete Society, London, England.

4. Peabody, A. W., Control of pipeline corrosion, National Association of Corrosion Engineers, Houston, 1967.
5. Elliott, J. F., Monitoring Prestressed Structures, Civil Engineering, July 1996, pp. 61-63.
6. Paulson, P., Continuous acoustic monitoring of suspension bridges and cable stays, Structural Materials Technology III: An NDT Conference, San Antonio, Texas, Proceedings of SPIE V. 3400, p. 205-213, 1998.
7. Travers, F.A., Acoustic Monitoring of Prestressed Concrete Pipe, Construction and Building Materials, Vol. 11, No. 3, pp. 175-187, 1997.
8. Mergelas, B.J. and Atherton, D.L., In-line electromagnetic inspection of PCCP, Pipelines in the Constructed Environment, American Society of Civil Engineers, Reston, Virginia, USA. p 714-720., 1998.
9. Sawade, G., et. al., Signal Analysis Methods for the Remote Magnetic Examination of Prestressed Elements, Proceedings of the International Symposium on Non-Destructive Testing in Civil Engineering, Sept. 26-28, 1995, p. 1077-1084, edited by G. Schickert, H. Wiggenger, DGZfP, 1995, Berlin
10. Scheel, H. and Hillemeier, B., Capacity of the remanent magnetism method to detect fractures of steel in tendons embedded in prestressed concrete, NDT & E International, vol. 30., no. 4, pp. 211-216, 1997.
11. Scheel, H. and Hillemeier, B., Magnetic detection of prestressing steel fractures in prestressed concrete, Materials and Corrosion, vol. 49, pp. 799-804, 1998
12. Atherton, D.L., Magnetic Inspection is key to ensuring safe pipelines, Oil and Gas Journal, vol 87, no. 32, pp. 52-61, 1989
13. Mandal, K. and Atherton, D.L., A study of magnetic flux leakage signals, J. Phys. D.: Appl. Phys., vol. 31, pp. 3211-3217, 1998.
14. Altschuler, E. and Pignotti, A., Nonlinear model of flaw detection in steel pipes by magnetic flux leakage, NDT & E International, vol. 28, no. 1, pp. 35-40, 1995.
15. Shannon, R.W.E. and Jackson, L., Flux leakage testing applied to operational pipelines, Materials Evaluation, vol. 46, pp. 1516-1524, 1988.
16. Hanasaki, K. and Tsukuda, K., Estimation of defects in a PWS rope by scanning magnetic flux leakage. NDT & E International, vol. 28, no. 1, pp. 9-14, 1995.
17. Kalwa, E. and Piekarski, K., Qualitative and Quantitative Determination of Densely Occurring Defects in Steel Ropes by Magnetic Testing Method, Materials Evaluation, vol. 46, pp. 767-770, May 1988.

18. Ghorbanpoor, A., Magnetic based NDE of steel in prestressed and post-tensioned concrete bridges, Structural Materials Technology III: An NDT Conference, San Antonio, Texas, Proceedings of SPIE V. 3400, p. 343-347, 1998.

Vitae

Jon Makar is a Research Officer with the National Research Council Canada's Institute for Research in Construction. His education includes a Bachelor's of Applied Science in Engineering Physics from the University of British Columbia and graduate degrees in Engineering Physics and Physics from Queen's University, Kingston, Ontario. Dr. Makar's research focuses on non-destructive evaluation and material science for infrastructure related problems. His current projects include work on inspection and monitoring techniques for prestressing steel, applications of the remote field effect and investigations of the failure process in cast iron pipes.

Richard Desnoyers is a Technical Officer with the Institute for Research in Construction. His education includes a Bachelor of Physics degree from the University of Toronto and a Mechanical Engineering Technology diploma from Algonquin College, Ottawa. In addition to working with Dr. Makar on NDE research, his other projects include the monitoring of strains in pipe liners and sidewalks.

Figures

1. Schematic diagram of the experimental apparatus in magnetic flux leakage mode. The yoke is used to magnetise the cables used in the residual field experiments, but the measurements are made on a single strand using the sensors shown without the yoke present.

2. Magnetising techniques used for residual field experiments. In each case the magnetisation procedure started by drawing the cable on to the yoke (Stage 1). The cable was then pulled along the yoke (Stage 2) until the end was reached (Stage 3). Two different procedures were then followed. The cable was either pulled directly away from the yoke (Stage 4a) or the cable was pulled off the magnet by continuing the movement in the same direction as the previous stages (Stage 4b).

3. A close up of the wire cable under investigation. Note that the wires of the cable have not been shown twisted about the cable's axis in order to clarify the drawing. The dashed area shows the plane of the measurements reported in the paper. The directions of the magnetic fields measured in that plane and axes used in the subsequent figures are also shown.

a)

b)

4. Three dimensional maps of the residual magnetic field produced using the “Stage 4a” magnetising technique near a 20 mm notch. Figure 4a: Axial Field. Figure 4b: Radial Field.

5. Axial, radial and circumferential field components at 2 mm from the cable using the same set of measurements shown in Figure 4. The circumferential results have been offset by -2 mT and the radial results by $+2$ mT for clarity.

a)

b)

6. The residual magnetic field at 20 mm and 50 mm from the cable. Figure 6a: axial component, Figure 6b: radial component. The degree values indicate the rotation of the notch in the cable from the plane of the sensor array.

7. Comparison of the results of multiple magnetising passes on the residual magnetic field measurements.

a)

b)

8. Three dimensional maps of the residual magnetic field produced using the “Stage 4b” magnetising technique near a 20 mm notch. Figure 8a: Axial Field. Figure 8b: Radial Field.

a)

b)

9. Residual magnetic field components measured at 2, 20 and 50 mm from the cable using the same measurements shown in Figure 8. Figure 9a: Axial Field, Figure 9b: Radial Field, Figure 9c: Circumferential Field

c)

9. (Continued) Residual magnetic field components measured at 2, 20 and 50 mm from the cable using the same measurements shown in Figure 8. Figure 9a: Axial Field, Figure 9b: Radial Field, Figure 9c: Circumferential Field

10. Magnetic flux leakage measurements made using the same yoke as the residual flux measurements show in previous Figures.