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Detection of rebar corrosion in concrete power poles

Joseph Bailey[1], Nick Long[1] and Gideon Gouws[2]

[1] Robinson Research Institute, Victoria University of Wellington
[2] Victoria University of Wellington

Presenter:

Joseph Bailey
Robinson Research Institute, Victoria University of Wellington

Abstract

A growing number of concrete power poles are reaching the end of their design life which will present a significant replacement cost in the coming years if they are replaced according to their design life. If it was possible to determine whether the rebar or pre-stressed wire in the poles had corroded it may be possible to keep these poles in service past their design life without an increase in risk. I have developed a non-destructive testing (NDT) system based on the eddy current principle. The system is composed of a large coil and an array of giant magneto resistance (GMR) sensors. Eddy currents are induced into the rebar and these currents produce a magnetic field which is measured with the GMR sensor array. When the rebar corrodes, conductive material is lost which distorts the eddy currents which in turn distorts the magnetic field. This distortion of the magnetic field can be used to determine if the rebar has corroded. Finite element modelling (FEM) results show how different levels of corrosion affect the magnetic field allowing a level of severity to be determined from field measurements. The FEM modelling also shows that excitation at different frequencies increases the size of the distortion produced by an area of corrosion. A system has been built to allow initial proof of concept testing. Two basic mock pole configurations were tested with the prototype system one with rebar and one with steel cable in a square pattern. Steel has been removed in a small patch to simulate the effect of corrosion. The results of testing with a prototype device on mock power poles, both mass-reinforced and pre-stress types, has shown that if 1-2mm of the steel has corroded an easily identifiable magnetic field signal is generated.

1 INTRODUCTION

1.1 THE PROBLEM

Concrete power poles have been used in New Zealand from before 1940 with a large number installed from the 1960’s and 1980’s with 537,000 installed in this period. They are now the predominant type of power poles in the New Zealand network with 980,000 installed out of a total number of 1,347,000 [1]. The reported design life of these power poles installed in the initial push between 1960’s and 1980’s is difficult to determine, as records are sparse, but 70-80 year life is thought of as a reasonable value. This means many concrete power poles are going to start reaching the end of their design life over the next 10-20 years. This will be a significant capital cost if these poles are replaced at the end of their 70 year design life. Assuming a pole replacement cost of $8000 a total expenditure of $370 million over the next decade can be expected, with that amount potentially tripling in the following decade. Some of this significant capital spend could be deferred if the poles integrity could be tested non-destructively to establish how much corrosion has occurred

Typically, when the rebar inside a concrete power pole corrodes the expansion of the corrosion will cause the concrete to spall as shown in Figure 1, giving a clear visual indication before the pole is in danger of collapse. However, some conditions exist when corrosion can progress to a dangerous level without any visual indications. This includes corrosion below the ground line, corrosion in hollow poles where the spalling can occur internally, corrosion in low oxygen environments where low volume corrosion products that are generated do not cause spalling. In some pre-stressed power poles small amounts of corrosion can also occur in the thin pre-stressing wires, reducing the strength to a point where the pole will fail unexpectedly without any outward indication.

Figure 1 Examples of spalling concrete power poles where the corrosion has expanded and caused the concrete to crack and fall off making a clear visual sign of an issue.[2]

A system that could quickly determine whether rebar is corroding in concrete power poles, and to what extent, would provide a solution to these problems. It would identify issues early before dangerous conditions have occurred and would enable power poles to be used well beyond their design life by end of life testing to show no significant corrosion rusting has occurred.

1.2 WHAT IS CURRENTLY AVAILABLE

The standard approach for concrete power pole inspection is a visual inspection that looks at the extent of spalling that has occurred, cracks in the concrete and rust staining. Some NDT systems for wooden poles exist such as the Portascan[3], Polescan[4] and Deuar MPT system [5] but there is little research into NDT for concrete power poles. However, there is a range of techniques used to inspect larger concrete structures such as GPR(ground penetrating radar) and magnetic based systems have been investigated for bridges [6]–[11]. These systems however are typically not sensitive enough to identify corrosion pre-spalling which is what is needed for effective power pole inspection.

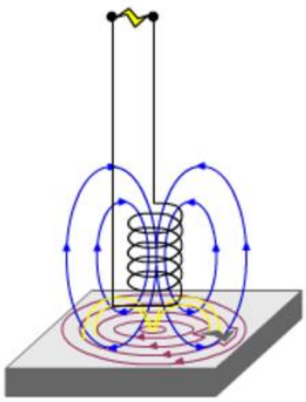
1.3 WHAT WE HAVE DEVELOPED

This paper presents research into an eddy current based NDT system that has the potential to detect diameter loss of 1 mm or less on rebar in concrete power poles. This is shown through FEM simulations and experiments on mock power poles with a prototype system that is ready for initial field trials.

2 EDDY CURRENT TESTING SYSTEM WITH ENCIRCLING COIL

2.1 EDDY CURRENT TESTING PRINCIPLES

Eddy current testing is a well-established NDT method that has been used since 1960's. The basic operation of an eddy current system is shown in Figure 2. An excitation coil generates a magnetic field shown by the blue lines. This generates an eddy current in nearby conductive objects such as rebar or steel plates. These eddy currents generate their own magnetic field shown by the yellow lines. The total magnetic field can then be measured, which is a combination of the blue and the yellow lines. If there is an area of oxidised metal which is not conductive, the eddy current is diverted. This diversion distorts the magnetic field generated by the eddy currents and it is this distortion in magnetic field that is used to identify corrosion with an eddy current testing system.



- *Figure 2 Eddy testing principles. Blue line = magnetic field generated by coil, red line = eddy current in test object, yellow lines = field generated by eddy currents [12]*

2.2 POWER POLE EDDY CURRENT TESTING SYSTEM

The eddy current system presented in this paper uses an encircling coil geometry where the coil is placed around the power pole. This enables the full circumference of the pole to be measured simultaneously, improving the inspection speed over a typical solenoid coil-based eddy current system. An array of GMR sensors, arranged in pairs at 5 degree intervals around the excitation coil, is used to measure the magnetic field in the radial and circumferential directions to the excitation coil. This arrangement of magnetic sensors gives the system a high spatial resolution not normally seen in coil sensor-based systems and enables the measurement of small diameter wire as is used, in pre-stressed power poles. Only the radial and circumferential fields are measured as it is in these directions that the largest variations caused by rust in rebar are observed. A CAD model of a prototype system is shown in Figure 3.

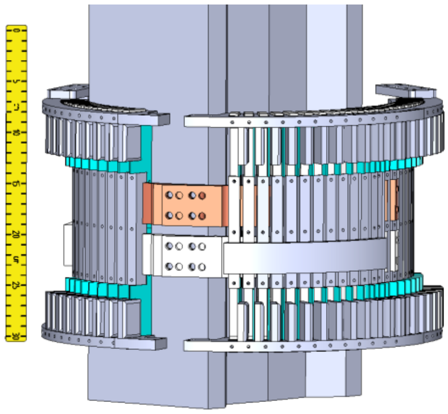


Figure 3 CAD drawing of eddy current testing tool with encircling coil and array of GMR sensors placed around a power pole. Excitation coil shown brown, blue shown PCB's containing magnetic sensors.

3 FEM SIMULATIONS OF POWER POLE INSPECTION

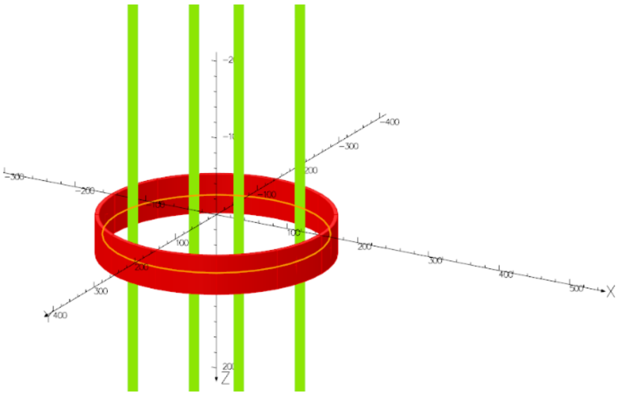
FEM simulations model complex systems by dividing the system into small elements and then using basic equations to find values of the parameters in that element such as the magnetic field or current. FEM has been used initially in this research as it allows rapid assessment of various parameters and the removal of real-world issues that can complicate the interpretation of results, all without having to build a physical system. This paper use simulations of a simplified model of a concrete power pole to investigate the effects of corrosion, tilting rebar and horizontal rebar.

3.1 POWER POLE NO RUST SIMULATION

The first simulation was a base simulation which could be used for comparison. It simulated a simplified rebar structure in a concrete power pole with 12 mm rebar placed at the corners of a 150 mm square. A 288 mm diameter coil was placed around the rebar to simulate a power pole with

25mm of concrete cover. This simulation layout is shown in Figure 4. The magnetic field along the centre line of the excitation coil was extracted from the simulation and a series of simulations were completed moving the coil in 5 mm steps up the length of the simulated power pole. The magnetic field from each of these simulations is then combined to form a map of the magnetic field over the surface of the power pole. This is then visualized as a contour map as seen in Figure 4 where X axis shows the location of the coil and the Y axis the position around the coil and with blue lines showing the location of the rebar. Only a quarter of the field is shown as the system is rotationally symmetric.

In Figure 4 we can see two weak peaks of 0.07 µT at the location of the rebar. These are a result of a simulation artefact due to boundaries. The simulated rebar is only 1 meter long to reduce the calculation time so some effect on the magnetic field is observed in these simulations. Ignoring these artefacts, the simulation shows there is no magnetic field in the radial direction if there is no defect and the rebars are vertical.



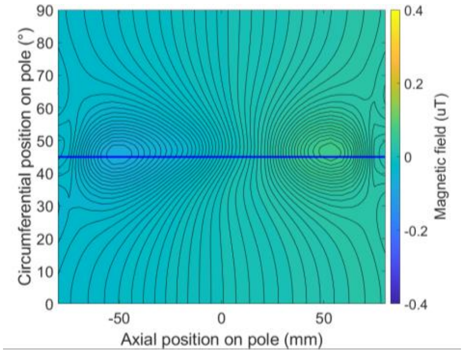
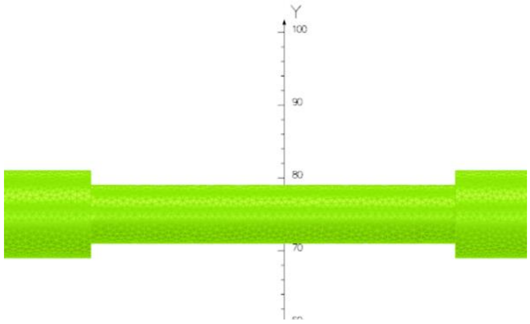


Figure 4: A) Layout of FEM simulation of simplified power pole. rebars shown in green, excitation coil shown in red and magnetic field measurement location shown by orange line. B) Contour map of radial magnetic field over the surface of simplified power pole with no corrosion. Blue line shows location of rebar.

3.2 BASIC REBAR PATTERN WITH CORROSION

To investigate the effect of corrosion on the magnetic field the base simulation from section 3.1 was repeated but with the diameter of the rebar reduced by 4 mm over a 50 mm section as shown in Figure 5. As rust has a similar conductivity to replacing the steel with air this has the same effect on the eddy current as rust. The resulting magnetic field contour map of the radial magnetic field is shown in Figure 5 with the red lines showing the location of the edges of the diameter reduction.



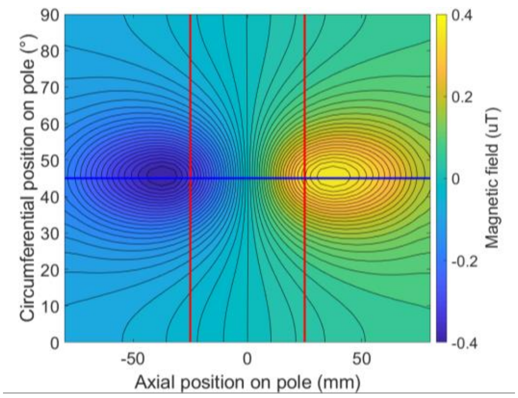


Figure 5 A) simulated corrosion 4mm rebar diameter reduction. B) Contour map of radial magnetic field over the surface of simplified power pole with corrosion. Blue line shows location of re-bar red lines the location of simulated corrosion.

Figure 5 shows the reduction in diameter generates 0.4 µT positive and negative peaks in the radial magnetic field approximately located where the diameter changes. therefore by measuring the radial magnetic field we can easily locate corrosion in vertical rebar.

To determine the sensitivity of the measurement the simulation was repeated for a range of changes in diameter. This allows a detection limit to be estimated for a given sensor sensitivity level. From each simulation the peak to peak value of the distortion in the radial magnetic field was extracted and is plotted against diameter change in Figure 6.

Figure 6 shows that even with only 0.5 mm of diameter reduction a field of 0.07 µT is generated which can be detected with commercially available sensors such as TMR2001 from Multi Dimension which would generate 30 µV for this reduction in magnetic field. It also suggests that the amount of diameter loss caused by corrosion could be estimated by measuring the peak to peak value in the magnetic field that is generated.

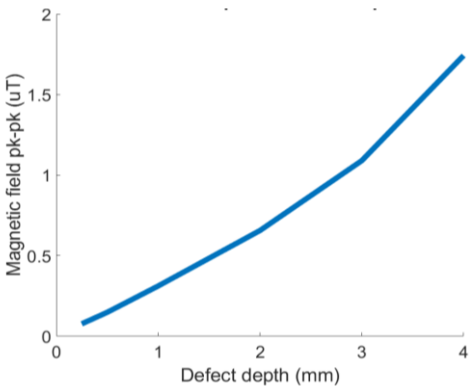


Figure 6 Effect the depth of corrosion in rebar on the magnitude of the magnetic field distortion

3.3 Effect of tilting the rebar

Almost all power poles have a taper and so the rebar is not vertical but tilted slightly from the vertical. The initial simulation modelled the rebar as perfectly vertical. However, it is important to understand the effect of tilting the rebar to determine if reduction in the diameter caused by corrosion can still be detected and to guide the development of a method to reduce the obscuring effect of non vertical rebar.

The simulation from section 3.1 and 3.2 the simulation with and without a rebar diameter reduction have been repeated, but with the addition of a 1.5° tilt from vertical to the rebar. The resulting contour plots of the radial magnetic fields are shown in Figure 7. Instead of the zero field background that was shown in Figure 6 for a rust free rebar, Figure 7 shows that when the rebar is tilted, the magnetic field is increased as the distance between the excitation and the rebar reduces, resulting in peaks at either end of the rebar. However, these peaks are only 0.07 µT so when we look at the simulation with the diameter reduction in Figure 7 the same easily identifiable peaks in the radial magnetic field are seen that were observed for the vertical rebar in Figure 6. This shows that the non-vertical nature of rebar in power poles should not stop the detection of corrosion, at worst case it will slightly increase the minimum detectable change in diameter.

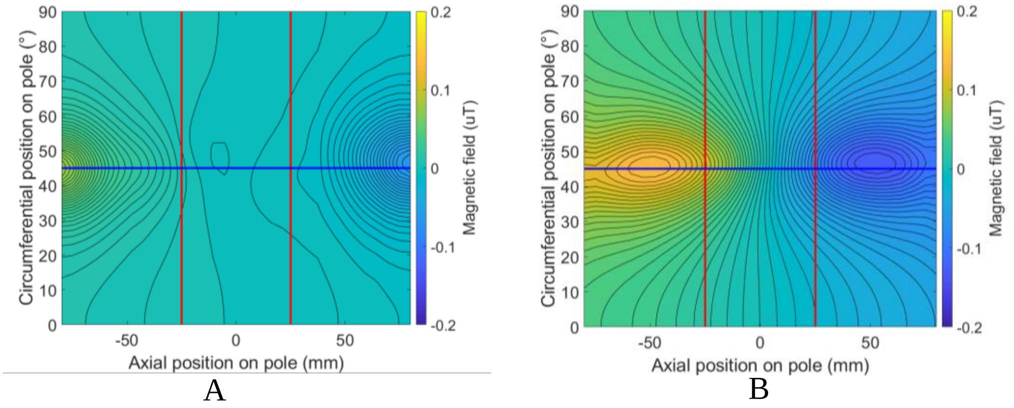


Figure 7 radial magnetic field contour over basic power pole with 1.5° tilt on rebar. Red lines show the edge of diameter reduction and blue line the location of the rebar. A) no diameter reduction B) 4mm diameter reduction

3.4 EFFECT OF REBAR INTERSECTIONS

Often the rebar inside concrete power poles has a loop of horizontal rebar, for example to form the hip. This addition of steel will make defects nearby to these horizontal elements considerably harder to detect. To quantify this issue, the simulations for section 3.1 and 3.2 were repeated but this time with a 12 mm hoop of rebar around the vertical section rebar. The area of diameter reduction directly behind the rebar was increased to a length of 80 mm and a diameter reduction of 4 mm as shown in the simulation setup in Figure 8. Figure 9 show the radial magnetic field for each of these simulations. The dominant features are two large peaks in the magnetic field generated by the horizontal rebar, making it hard to identify the effect of the diameter reduction on the magnetic field. To determine the effect of the defect on the magnetic field the difference between the two simulations is calculated and plotted in Figure 9. This shows there is an effect from the defect. However, if defects behind horizontal rebar need to be identified then better data processing systems will need to be developed that can remove the effects of the horizontal rebar on the magnetic field.

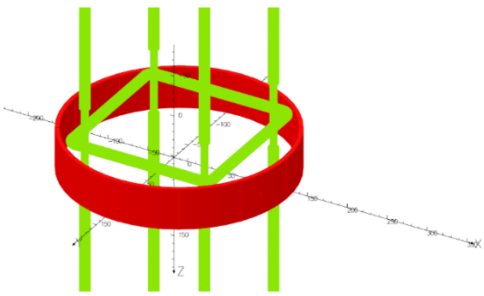
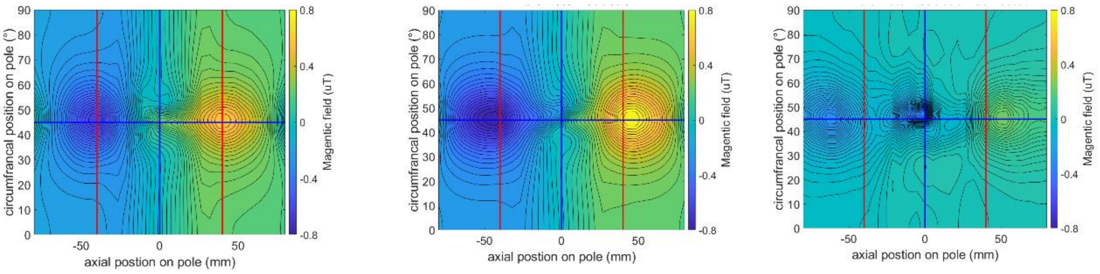


Figure 8 Simulation layout of power pole with hoop of horizontal rebar. rebar shown in green and excitation coil shown in red



A B C

Figure 9 Radial magnetic field over simulated power pole with horizontal hoop of rebar with blue lines showing location of rebar and red lines the edge of rebar diameter reduction. A) no diameter reduction B) 4mm diameter reduction C) difference between field with and without diameter reduction.

4 EXPERIMENTS

4.1 FIELD PROTOTYPE

To test these simulations in the real world a prototype system has been built which is pictured in Figure 10. It consists of a solid copper ring as the excitation coil with transformer and power amplifier enable current up to 600 A to be generated in the coil. An array of 96 magnetic sensors have been placed around the ring measuring the magnetic field in the radial and circumferential direction at five degree intervals. A lifting system has been built for testing on infield poles, but the testing present here has been completed in the lab on mock power poles.

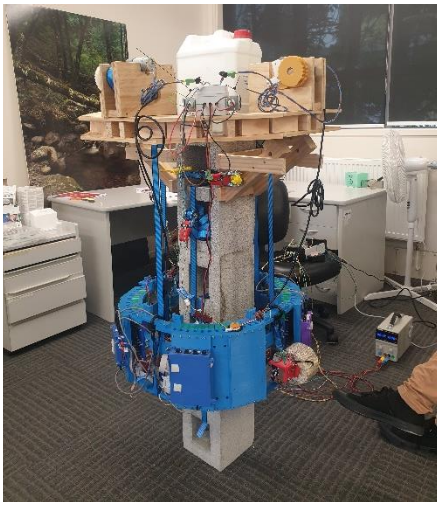


Figure 10 Prototype system for field testing eddy current testing of concrete power poles

4.2 TEST ON REBAR

The first test with the prototype system was on a basic mock mass-reinforced concrete power pole. A polystyrene former was used to hold four 12 mm rebars vertical at the corners of a 150 mm square. The polystyrene was arranged to simulate a 50 mm concrete cover. The corrosion was simulated by reducing the diameter of the rebar in a 50 mm section by 1 mm and 2 mm with an angle grinder. The measured radial field for each of these simulated corrosion shapes is shown in Figure 11, with the red box showing the approximate. location of the diameter reduction and the blue lines showing the location of the rebar.

Figure 11 show clear peaks in the radial magnetic field against a near zero background magnetic field as was predicted by the simulations in section 3.2. In addition, the large diameter reduction produced larger peaks again as expected from the simulations. This result shows both that the simulation methodology is effective in predicting the magnetic field and that small changes in the rebar diameter can be easily be detected by an eddy current testing prototype without any requirement for data-processing or identification algorithms.

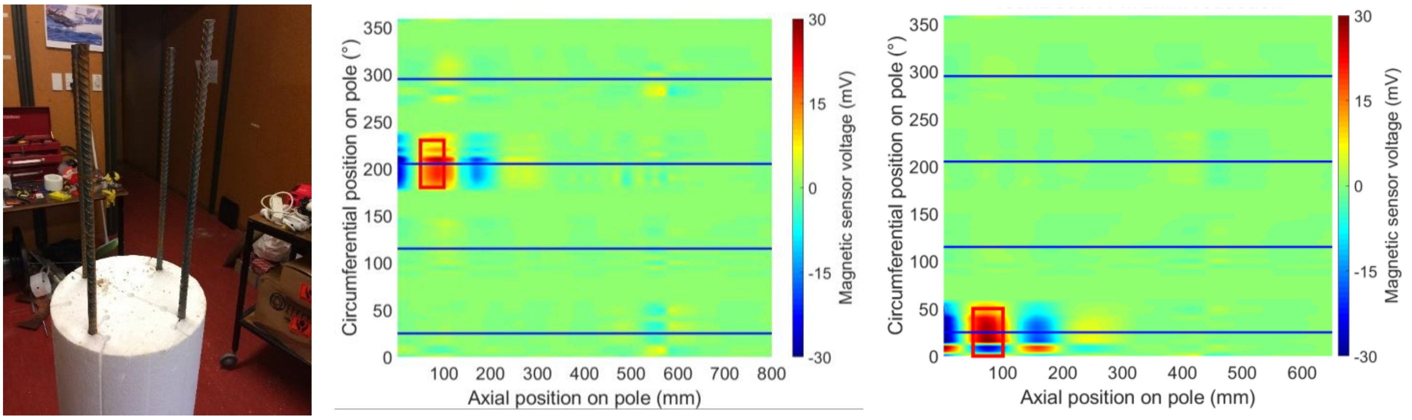


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Figure 11 A) Mock mass reinforced concrete power pole with polystyrene replacing concrete. B) Radial magnetic field of mock power pole with 1 mm diameter reduction C) radial magnetic field mock power pole with 2 mm diameter reduction. Red box shows location of diameter reduction.

4.3 TESTING ON WIRE ROPE

As mentioned in section 1.1 prestressed concrete power poles are particularly exposed to failure without the pre-warning that concrete spalling provides. A similar method to that in section 4.2 was used to make a mock prestressed power pole to test with the prototype system. Instead of 12 mm rebar, 7.5 mm wire rope was used, spaced out by polystyrene on the corners of a 110 mm by 190 mm rectangle. The wire was tensioned so that it was straight. The prototype system was placed on the mock power pole and moved down its length as seen in Figure 12. The corrosion was simulated by using a file to remove 50 % or 80 % of one strand. The radial magnetic field measured on these two mock prestressed power poles is shown in Figure 15.

Figure 12 Experimental setup for testing mock pre-stressed power pole with eddy current testing system

Figure 15 show peaks in the magnetic field at the location of the defects as seen in the experiments on the mock mass reinforced power pole in section 4.2. However, the peaks are now smaller in amplitude and extent. This is likely due to two reasons. Firstly the small diameter wire means only one to two sensors will pass closely over the top of the wires limiting the extent of the peaks in the circumferential direction. Secondly as the diameter is smaller it means less steel is removed and so less eddy current is distorted which would result in smaller peak amplitudes.

We can also note that while the 80% strand loss generates a peak larger than the background field variations. However, this is not true for the 50% stand loss which means a 50% strand loss or less would not be detectable with the prototype system in its current state. This could be improved in the future a more stable movement system that will not introduce as much noise into the system.

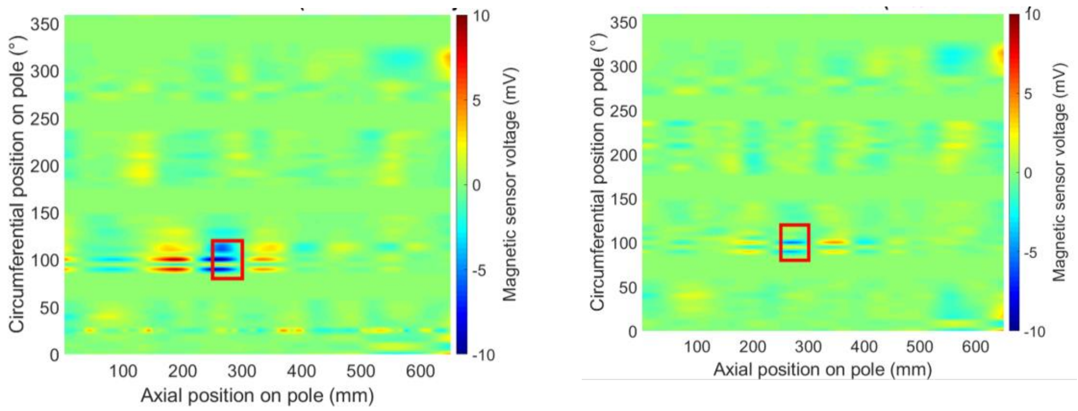

Figure 13 Circumferential magnetic field over mock pre-stressed power pole with simulated corrosion location shown by red box. A) 80% strand loss. B) 50% strand loss

5 DISCUSSION

The major remaining technical issue to resolve with this eddy current testing system to enable its use across a wide range of concrete power pole styles is accounting for the effect of closely spaced or intersecting rebar. This paper has shown the issues that appear when a horizontal rebar intersects with a vertical bar. It would be expected that similar issues may occur when the rebar is tightly spaced, as the magnetic field from neighbouring rebar will influence each other.

To improve the accuracy of sizing of the corrosion area further work is required determining the effect of shape of the defect. The work so far has shown there appears to be a relationship between the volume of steel converted to rust and the amplitude of the distortion but there are likely other parameters that affect this that will need to be accounted for.

6 CONCLUSIONS

FEM and experiments have shown that reduction in rebar diameter of 30% can be detected with the eddy current testing system presented here with the potential for much smaller reductions to be detected. When the rebar diameter changes a peak in the radial magnetic field is generated, enabling the identification of the defects. There appears to be a relationship between the volume of steel loss and amplitude of the distortion in the magnetic field which allows the extent of corrosion to be estimated. FEM simulations have shown tilting the rebar a few degrees from vertical does not significantly affect the ability to detect defects. However, the introduction of horizontal rebar does affect the ability to detect defects. The FEM simulations have shown that there is a measurable change in magnetic field generated by the defect in this situation, but further research is required to determine how to identify this distortion as it is smaller than the distortion generated by the horizontal rebar.

7 REFERENCES

[1] "Performance accessibility tool - New Zealand electricity distributors - Data and metrics - Commerce Commission New Zealand | Tableau Public." https://public.tableau.com/profile/commerce.commission#!/vizhome/Performanceaccessibilitytool-NewZealandelectricitydistributors-Dataandmetrics/Homepage (accessed May 05, 2021).

[2] "CFRP & Concrete Ultility Poles," *H & N Fiberworx*. http://www.fiberworx.ca/cfrp-concrete-utility-poles/ (accessed May 05, 2021).

[3] G. Wallace, "PortaScan: a new instrument for NDE of wooden structures," *N. Z.*, p. 6, 2006.

[4] "IAMSL :: Polescan." https://www.polescan.com/polescan/ (accessed May 05, 2021).

[5] "Deuar - Pole Inspection and Mechanical Pole Testing Method (MPT)." http://deuar.com/index.htm (accessed May 05, 2021).

[6] D. Eisenmann, F. Margetan, C.-P. T. Chiou, R. Roberts, and S. Wendt, "Ground penetrating radar applied to rebar corrosion inspection," Denver, Colorado, USA, 2013, pp. 1341–1348, doi: 10.1063/1.4789198.

[7] C. C. H. Lo and N. Nakagawa, "Evaluation of eddy current and magnetic techniques for inspecting rebars in bridge barrier rails," Denver, Colorado, USA, 2013, pp. 1371–1377, doi: 10.1063/1.4789202.

[8] B. Fernandes, D. Nims, and V. Devabhaktuni, "Comprehensive MMF–MFL inspection for corrosion detection and estimation in embedded prestressing strands," *J. Civ. Struct. Health Monit.*, vol. 4, no. 1, pp. 43–55, Feb. 2014, doi: 10.1007/s13349-013-0061-4.

[9] H. Zhang, L. Liao, R. Zhao, J. Zhou, M. Yang, and R. Xia, "The Non-Destructive Test of Steel Corrosion in Reinforced Concrete Bridges Using a Micro-Magnetic Sensor," *Sensors*, vol. 16, no. 9, p. 1439, Sep. 2016, doi: 10.3390/s16091439.

[10] D. He, "Evaluation of Steel Rebar in Concrete Using Electromagnetic Method," *Fail. Anal.*, Jun. 2019, doi: 10.5772/intechopen.86668.

[11] K. Myakushev, D. Slesarev, and D. Sukhorukov, "Magnetic flux leakage (MFL) method for nondestructive testing of pre- stressed steel reinforcement strands," p. 3.

[12] "Basic Principles of ET." https://www.nde-ed.org/EducationResources/CommunityCollege/EddyCurrents/Introduction/IntroductiontoET.htm (accessed Jul. 08, 2020).