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A Simulation and Experimental Study Investigating 2D Magnetic Flux Leakage (MFL) for Defects in Reinforcing Steel

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ABSTRACT. *The study examines magnetic flux leakage signals (B_x, B_y) within D_{19} sized rebars in two dimensions. An economically designed test setup incorporating permanent magnets was used to collect magnetic flux leakage at the defect location. The numerical simulation was performed using COMSOL Multiphysics on a 2D finite element model. This study also attempts to enhance defect analysis by using the MFL signals (B_x, B_y). As defect width increases, the x-component of the signal (B_x) increases, and with depth, the y-component (B_y) increases. Even though depth and width interact in signal appearance, the overall amplitude variation was sufficient to predict the defect area. R^2=0.9079 indicates a higher coefficient of regression for x-component (B_x) amplitudes in defect areas. A positive correlation between defect position, geometry, and shape was found.*

Keywords: Defect size, Magnetic flux leakage, Sensors, Reinforcing steels

1. INTRODUCTION

Bridges, buildings, and other reinforced concrete structures need to detect embedded reinforcing steel defects in order to maintain and repair them. Researchers around the world are working on detecting and quantifying unnoticed deteriorated patches in reinforced concrete members. Constructions that are exposed to the environment are more likely to have corrosion of reinforcement that affects their capacity and service life [1].

It is becoming more popular to conduct non-destructive testing (NDT), and magnetic flux leakage (MFL) is one of the most promising techniques. The technology has been applied to the testing of pipelines [2], inspection of plates [3], tubes [4], wire ropes testing [5], rail tracks crack inspection [6], storage tank floors [7], and the testing of suspension bridge cables [8]. Furthermore, qualitative approaches have been used to detect, evaluate, and monitor the damage level in steel reinforcement. Using the electromagnetism theory, defects can be assessed by comparing steel's and concrete's magnetic properties. In the case of reinforced concrete, evaluating signal behavior based on defects in reinforcing steel remains a challenge. Working test setups typically utilize Hall-effect sensors to establish a correlation between corrosion and magnetic flux change (signals of mass loss). Magnetic flux density and mass loss have been connected in various studies, voltage and mass loss have been links, and self-magnetic flux leakage and bending strength of corroded reinforced beams have been studied [9]. A partial modulus and magnetic gradient indicator for monitoring reinforcement bar corrosion, a magnetic flux leak detector to detect localized corrosion cross-sections and a 3D laser scanner for determining reinforcement conditions are all tools to utilize for monitoring reinforcement bar corrosion. Analyzing lift-off variation from metal to detect defects, an electromagnetic apparatus is developed to monitor reinforcement bars through Hall-effect sensors [10], [11].

This work mainly describes quantitative approaches for analyzing reinforced steel defects using an MFL-based setup that is cost-effective. The main objective of this study is to identify defect regions and to analyze the size of defects using sensor signals components (B_x, B_y).

2. METHODS

2.1 Numerical Simulation

A series of numerical simulations in the x- and y-directions (B_x, B_y) was conducted in this study to determine how defects affect those magnetic field components. As shown in Table 1, the numerical model has variables that are associated with defect types and their sizes.

Table 1. Numerical simulations main variables (D_{19})

Case		Dimensions of defects	
		Width dimension (mm)	**Depth dimension (mm)**
New	Type A	0	0
Defects from Cutting	Type 1	2	2
	Type 2	2	5
	Type 3	2	10
	Type 4	5	2
	Type 5	5	5
	Type 6	5	10
	Type 7	10	2
	Type 8	10	5
	Type 9	10	10

Validation of experimental test results has been carried out with COMSOL Multiphysics simulations. The 2D modelling was performed using COMSOL, resulting in magnetic flux density leakage at every millimeter using different defect types and permanent magnets. COMSOL Multiphysics v5.5 has been used to study AC/DC modules. An example of a mesh analysis and results based on a defect size of 5X5 (width x depth) can be seen in Figure 1. As a result of selecting the magnetization model, the magnetic flux leakage at the defect location is analyzed as follows.

$$B = \mu_0 (H+M) \qquad (1)$$

In equation 1, B represents the magnetic flux density, H represents the strong magnetic field of the magnet, M represents the magnetic field induced in the specimen, and μ_0 represents the relative permeability of the materials. Basically, it works on the principle that when a magnetic field (H) is applied to a ferromagnetic material, magnetization fields (M) develop on the specimen; these fields cause leakage at defect locations due to differences in permeability (μ_0).

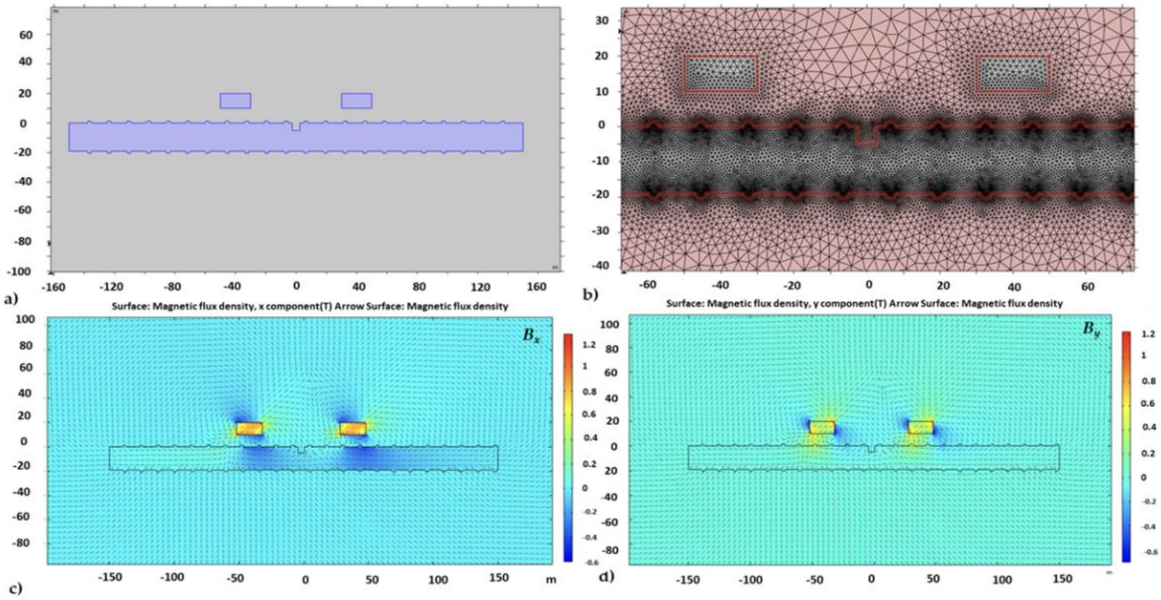

Fig -1: Finite element model (FEM) for simulation of magnetic flux leakage components (B_x, B_y) in reinforcement steel with a defect size of 5X5.

2.2 Experimental Work

A cost-effective test setup was developed using various non-ferrous materials and electronic devices. An Arduino UNO is used to program the system, single and triple-axis magnetic field sensors to measure magnetic field leakage, as well as an LCD to display real-time signals data as shown in the Figure 2.

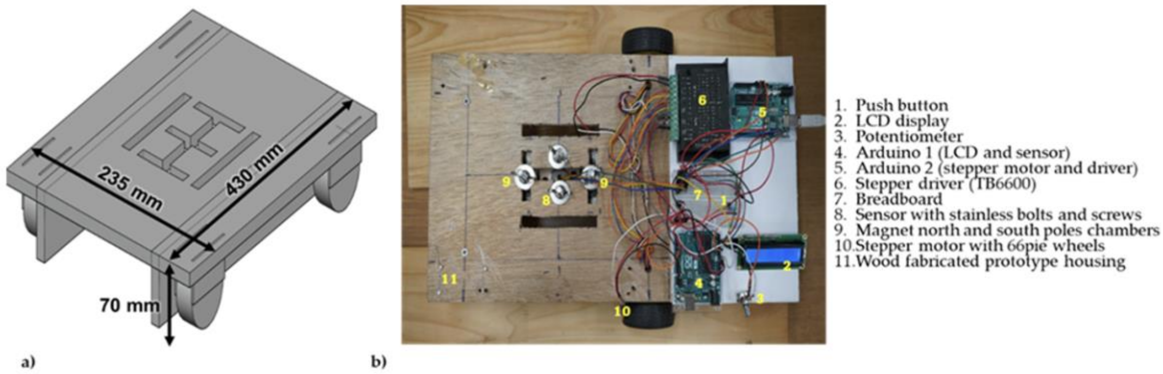

Fig -2: Experiment work setup: (a) Housing model, (b) Test setup top view

3. RESULTS

The two components (B_x, B_y) of magnetic field leakage are determined by a 2D Finite Element Model (FEM) of reinforcing steel in COMSOL Multiphysics. A magnetic flux leakage measurement was taken every millimeter and every five millimeters in height according to the FEM simulation. For maximum sensitivity, all measurements are converted to a single unit (Gauss), which is also the smallest. For maximum sensitivity, all measurements are converted to a single unit (Gauss), which is also the smallest. The signals resulting from simulation are shown below in Chart-1.

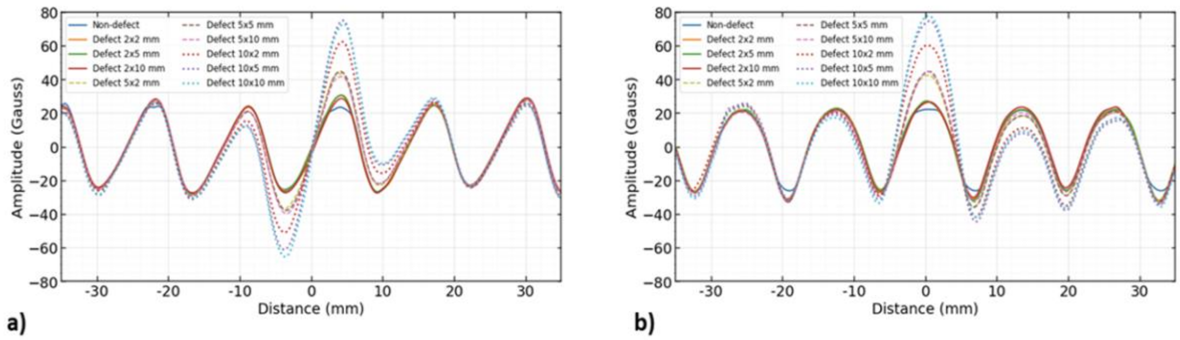

Chart -1: Numerically simulated results: (a) MFL x-component (B_x), (b) MFL y-component (B_y)

For each defect size, we received a magnetic flux leakage signal that we suspect contains information about the defect characteristics. In this case, the defect center is located at (0,0) with 35 points per millimeter around the defect center. Our work also investigated single and triple axis sensors used to measure changes in signal waveforms caused by saw cutting defects. With increasing defect size, the signals became stronger resulting in an increasing trend in signal strength. The signals resulting from experimental testing for x-components are shown below in Chart 2.

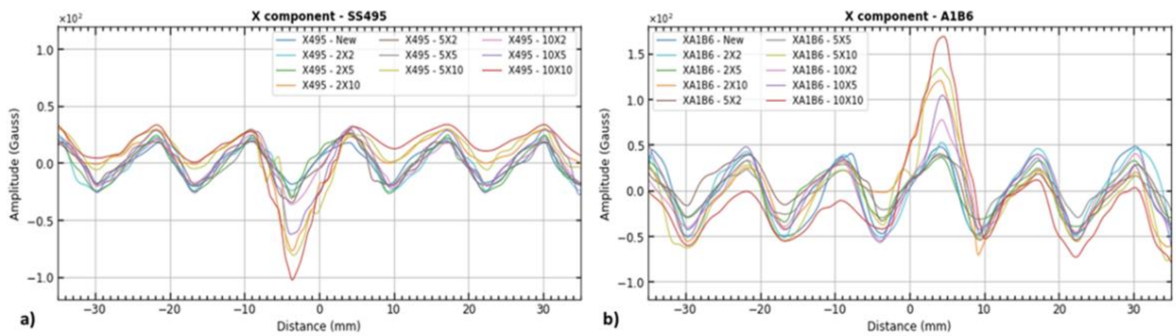

Chart -2: Experiment results: x-components signals with single and triple axis sensor

3.1 Effects of defect width and depth

The signal bandwidth of magnetic flux leakage x-component (B_x) is found to be correlated with defect width when each signal component is analyzed separately. Experiments shows that defect depth was associated with substantial changes in data. Sensors with single and triple axis both exhibit a similar upward trend with nearly identical slopes. During the evaluation of defect width, it is found that defect depth has an influence on the evaluation, making individual evaluation difficult. The three x-components are plotted as linear plots from the numerical model, the single-axis sensor (SS495), and the triple-axis sensor (A_1B_6). The trend of defect widths by signal bandwidth are shown in Chart-3.

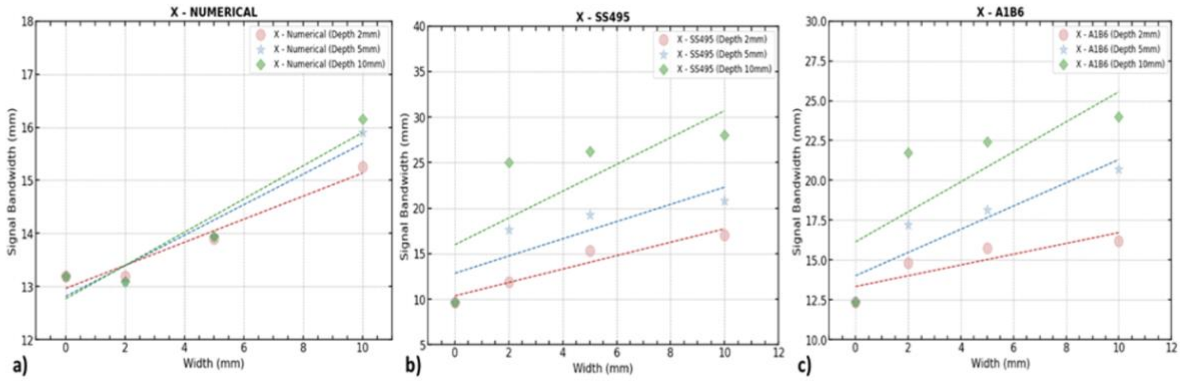

Chart -3: A trend of defect widths by signal bandwidth for x-components

It is determined that the y-component (B_y) of the magnetic flux leakage is well correlated with defect depth when looking at the defect depth analysis. In a manner similar to the width evaluation, linear regression plots illustrate the increasing trend of defect depth as a function of y-component of magnetic flux leakage (B_y) from the numerical model and triple axis sensor.

Data trends for defect depth were significantly affected by defect width in the numerical model (Chart -4a). A defect wider than 5mm significantly alters signals in the experimental three-axis sensor with a y-component (B_y). Accordingly, amplitudes for 2mm and 5mm widths range from 30 to 80, while amplitudes for widths of 2mm and 5mm range from 65 to 141 (Chart -4b).

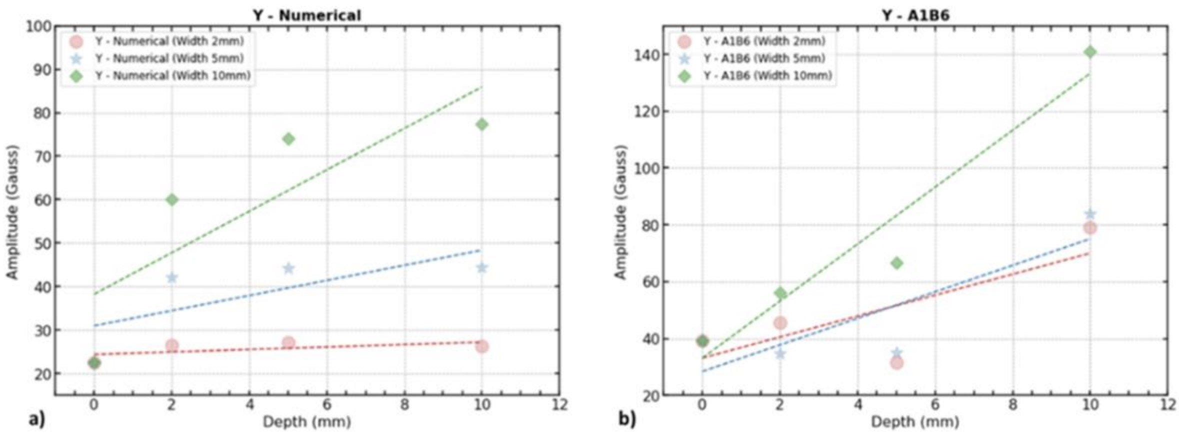

Chart -4: A trend showing defect depth in the signal's y-component (B_y).

3.2 Defect area evaluation

A correlation has been shown in Chart -5 between amplitude and bandwidth data for single and triple-axis sensor components. A regression coefficient (R^2 = 0.9079) is shown in Chart 5a, indicating that the amplitude of the triple-axis sensor with x-component (B_x) has the highest regression coefficient than the amplitude of the single-axis sensor (R^2 = 0.6229) and the amplitude of the triple-axis sensor with y-component (R^2 = 0.5918). In Chart 5b, lower regression coefficients were found for bandwidth than amplitude for two components of the triple-axis sensor. As shown in Chart 5a, defect areas are characterized by the amplitude of signal waveforms from the x-component of triple-axis sensor.

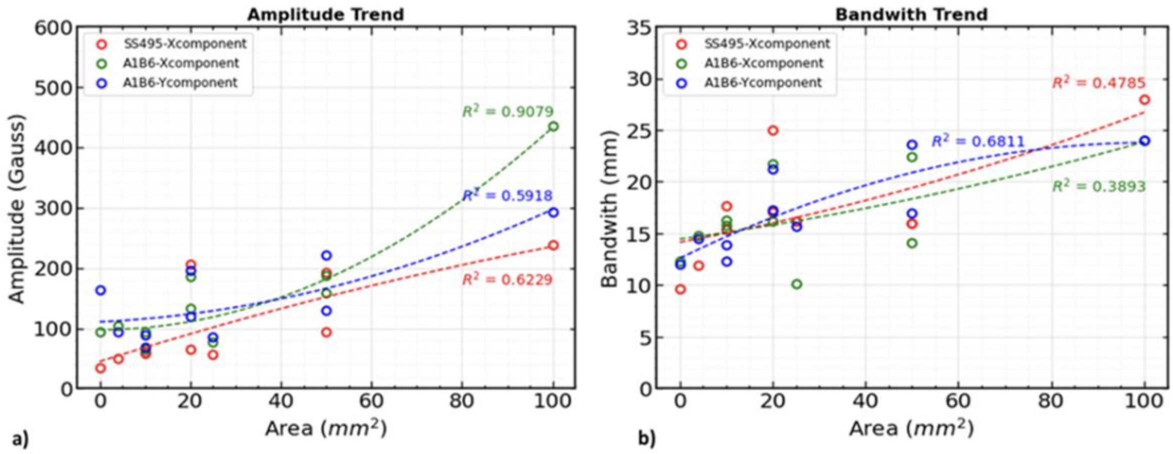

Chart -5: Correlation between defect areas and MFL signal amplitude and bandwidth.

4. CONCLUSIONS

Based on the results of this study, MFL has been demonstrated to be an efficient method for evaluating the size of defects in reinforcing steel.

1. Bandwidth of the x-component of the signal (B_x) correlates with defect width. In the case of increasing depth, it corresponds to the amplitude of the y-component (B_y).
2. The width and depth affect each other in the two-dimensional defects and cannot be assessed separately. An x-component (B_x) amplitude of a 3-axis sensor signal shows a higher regression coefficient (R^2=0.9079) in defect areas.

Using electromagnetism theory for embedded reinforcing steel under various concrete cover thicknesses, these results show the preliminary work for corrosion detection and quantification methods using MFL technique.

REFERENCES

[1] Page CL, Treadaway KW. Aspects of the electrochemistry of steel in concrete. Nature. 1982 May 13;297:109-15.
[2] Verma SK, Bhadauria SS, Akhtar S. Monitoring corrosion of steel bars in reinforced concrete structures. The scientific world journal. 2014 Jan 1;2014.
[3] Kordatos EZ, Strantza M, Soulioti DV, Matikas TE, Aggelis DG. Combined NDT methods for characterization of subsurface cracks in concrete. InSmart Sensor Phenomena, Technology, Networks, and Systems 2011 2011 Apr 15 (Vol. 7982, pp. 276-281). SPIE.
[4] Washer G, Bolleni N, Fenwick R. Thermographic imaging of subsurface deterioration in concrete bridges. Transportation research record. 2010;2201(1):27-33.
[5] Vedalakshmi R, Balamurugan L, Saraswathy V, Kim SH, Ann KY. Reliability of galvanostatic pulse technique in assessing the corrosion rate of rebar in concrete structures: Laboratory vs field studies. KSCE Journal of civil engineering. 2010 Nov;14:867-77.
[6] Xia R, Zhou J, Zhang H, Liao L, Zhao R, Zhang Z. Quantitative study on corrosion of steel strands based on self-magnetic flux leakage. Sensors. 2018 May 2;18(5):1396.
[7] Sun Y, Kang Y. Magnetic mechanisms of magnetic flux leakage nondestructive testing. Applied Physics Letters. 2013 Oct 28;103(18):184104.
[8] Suresh V, Abudhair A. Dipole model to predict the rectangular defect on ferromagnetic pipe. Journal of Magnetics. 2016;21(3):437-41.
[9] Fernandes B, Titus M, Karl Nims D, Ghorbanpoor A, Devabhaktuni V. Field test of magnetic methods for corrosion detection in prestressing strands in adjacent box-beam bridges. Journal of Bridge Engineering. 2012 Nov 1;17(6):984-8.
[10] Diederich H, Vogel T. Evaluation of reinforcing bars using the magnetic flux leakage method. Journal of Infrastructure Systems. 2017 Mar 1;23(1):B4016001.
[11] Mosharafi M, Mahbaz SB, Dusseault MB. Bridge deck assessment using infrastructure corrosion assessment magnetic method (iCAMM™) technology, a case study of a culvert in Markham city, Ontario, Canada. NDT & E International. 2020 Dec 1;116:102356.