

Magnetic Flux Leakage Device for Evaluation of Prestressed Concrete Box Bridges

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<p>Abstract:</p> <p>Corrosion of prestressed concrete reinforcement in bridge components is a major concern for state transportation agencies. The severity of the problem is amplified by the fact that the corrosion-induced damage in concrete reinforcement often does not show up on the surface until significant propagation has occurred. Moreover, prestressed reinforcement can undergo brittle fracture at lower cross-sectional losses when compared to nonprestressed reinforcement. As evidence, some prestressed bridges in Virginia built since the 1960s have begun showing premature corrosion-induced deterioration. This created a need for a nondestructive evaluation technique that could reasonably determine areas of damage at early stages of corrosion.</p> <p>Since a ready-to-implement commercial tool is not available, a prototype for a new magnetic flux leakage (MFL) device for the evaluation of hidden prestressing strand under the surface of prestressed concrete box beams was designed, developed, and tested in the laboratory. This device works based on the MFL principles of nondestructive evaluation. The novel features of this device are portability, lower cost, and real-time results, and it can be used by a bridge inspector with minimal training. The device uses advanced sensors and microcontroller technologies to deliver a battery-powered MFL inspection system device capable of detecting corrosion damage in prestressing strand beneath 2 in of concrete cover.</p> <p>The device was verified to work well in the laboratory and was minimally deployed in the field to check for any issues. An extension of the study could improve the field-implementable device to include better display of magnetic flux data and semi-automation to identify corroded areas of box beams. However, further improvement of the device in terms of analyzing and displaying results and fabricating a lighter, portable, self-containing instrument was beyond the scope of the Virginia Transportation Research Council in terms of resources. Therefore, the Virginia Transportation Research Council should propose a research needs statement and seek proposals for a follow-up study using implementation or other sources of funding to improve the device in terms of analyzing and displaying results and fabricating a lighter, more portable, self-containing instrument for field deployment for inspecting bridges in service.</p> <p>Condition evaluation of the prestressing strands in the box beams prior to severe corrosion-induced damage will lead to informed decision-making regarding whether to repair, replace a single beam, or replace the entire superstructure. This device can provide an indication of section losses in prestressed strands in areas with shallow concrete cover, where no off-the-shelf inspection equipment can provide this critical information on the condition of prestressed box beams. This makes the outcome of this study highly significant for the infrastructure of the Virginia Department of Transportation. Implementation of this technology will lead to improved safety of the traveling public, better performing box beam bridges, and cost savings to the Virginia Department of Transportation from making appropriate maintenance decisions.</p>				

FINAL REPORT
**MAGNETIC FLUX LEAKAGE DEVICE FOR EVALUATION OF PRESTRESSED
CONCRETE BOX BRIDGES**

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Virginia Transportation Research Council
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

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ABSTRACT

Corrosion of prestressed concrete reinforcement in bridge components is a major concern for state transportation agencies. The severity of the problem is amplified by the fact that the corrosion-induced damage in concrete reinforcement often does not show up on the surface until significant propagation has occurred. Moreover, prestressed reinforcement can undergo brittle fracture at lower cross-sectional losses when compared to nonprestressed reinforcement. As evidence, some prestressed bridges in Virginia built since the 1960s have begun showing premature corrosion-induced deterioration. This created a need for a nondestructive evaluation technique that could reasonably determine areas of damage at early stages of corrosion.

Since a ready-to-implement commercial tool is not available, a prototype for a new magnetic flux leakage (MFL) device for the evaluation of hidden prestressing strand under the surface of prestressed concrete box beams was designed, developed, and tested in the laboratory. This device works based on the MFL principles of nondestructive evaluation. The novel features of this device are portability, lower cost, and real-time results, and it can be used by a bridge inspector with minimal training. The device uses advanced sensors and microcontroller technologies to deliver a battery-powered MFL inspection system device capable of detecting corrosion damage in prestressing strand beneath 2 in of concrete cover.

The device was verified to work well in the laboratory and was minimally deployed in the field to check for any issues. An extension of the study could improve the field-implementable device to include better display of magnetic flux data and semi-automation to identify corroded areas of box beams. However, further improvement of the device in terms of analyzing and displaying results and fabricating a lighter, portable, self-containing instrument was beyond the scope of the Virginia Transportation Research Council in terms of resources. Therefore, the Virginia Transportation Research Council should propose a research needs statement and seek proposals for a follow-up study using implementation or other sources of funding to improve the device in terms of analyzing and displaying results and fabricating a lighter, more portable, self-containing instrument for field deployment for inspecting bridges in service.

Condition evaluation of the prestressing strands in the box beams prior to severe corrosion-induced damage will lead to informed decision-making regarding whether to repair, replace a single beam, or replace the entire superstructure. This device can provide an indication of section losses in prestressed strands in areas with shallow concrete cover, where no off-the-shelf inspection equipment can provide this critical information on the condition of prestressed box beams. This makes the outcome of this study highly significant for the infrastructure of the Virginia Department of Transportation. Implementation of this technology will lead to improved safety of the traveling public, better performing box beam bridges, and cost savings to the Virginia Department of Transportation from making appropriate maintenance decisions.

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FINAL REPORT

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INTRODUCTION

Background

The need to detect and quantify hidden deterioration of prestressing strand for in-service prestressed concrete bridges was identified as a high priority research need by the Virginia Transportation Research Council (VTRC). This need has also been identified by many other agencies, and there have been many research projects focused on developing methods and tools to meet this need. Several studies have investigated this topic in detail, and an inspection system capable of detecting damage to steel elements in concrete was developed. The feasibility of using the magnetic flux leakage (MFL) method to inspect prestressing strands in concrete was confirmed. However, the system developed was large and sophisticated and could not be readily implementable as an inspection tool (Ghorbanpoor et al., 2000; Jones et al., 2010; Niroumand et al., 2009).

The Virginia bridge inventory contains more than 750 prestressed concrete slab or box beam bridges. Assuming a 4-ft-wide beam and one precast unit per span, the total number of prestressed box beam units that need to be inspected is more than 12,000.

There have also been many technological advances in micromechanical systems and sensor technology over the last decade. It was desired to take advantage of these advances in designing and implementing a tool to meet the identified need.

Motivation

MFL is a mature method of non-destructive evaluation in many industries. It is routinely used to test the wire rope cables on elevators and industrial hoists. It is also routinely used to inspect pipelines and storage tanks for loss of metal attributable to corrosion. Several studies have produced prototype systems based on the use of MFL to inspect prestressed concrete slabs and beams. The basic principle is fairly straightforward and easy to understand; however, the

design and implementation are difficult because of the somewhat iterative nature of the design process.

Several criteria were identified in this study as essential or very important for a useful tool based on the use of the MFL method to inspect prestressing strand on prestressed box beams.

Basic Theory

In the presence of a strong magnetic field imposed on a magnetic material, the magnetic flux is concentrated in the magnetic material. If the magnetic material has locations where there is significantly less material, the magnetic flux will “leak” out of the material. Special sensors, usually Hall effect sensors, detect this flux leakage. Loss of metal section attributable to corrosion can be detected this way.

Ferromagnetic materials, such as steel, exhibit a highly nonlinear relationship between the strength of the magnetizing force and the corresponding flux density. The relationship between magnetizing force, measured in units of ampere-turns, and magnetic flux density, measured in teslas (T), is somewhat analogous to the stress-strain curve relationship familiar to most civil engineers. Some typical magnetic field strength flux density curves for different materials are shown in Figure 1.

Magnetic saturation, where there is no further increase in flux density with an increase in magnetic field strength, is clearly observed for steel. The key to a successful MFL application is to saturate the magnetic material. With saturation, significant leakage of flux will occur if metal is lost. Steel becomes saturated in a magnetic field with a flux density of approximately 1.4 T. It is assumed that prestressing strand has the magnetization hysteresis properties of very low carbon steel.

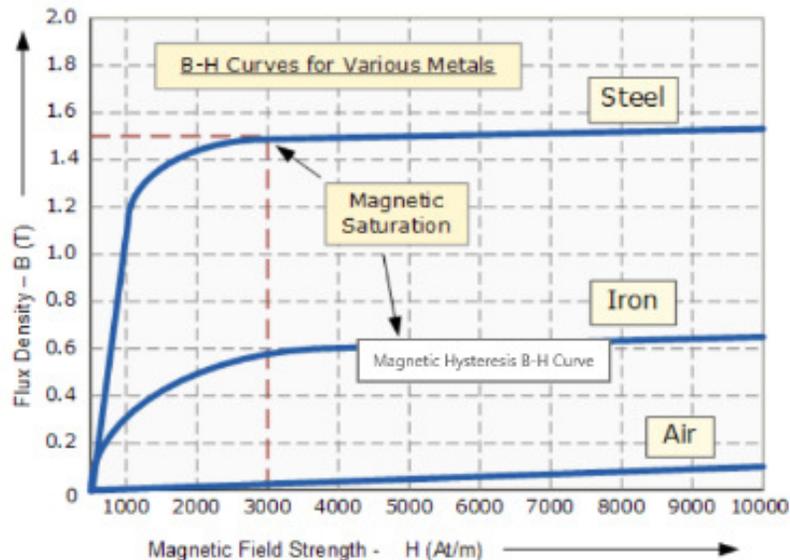


Figure 1. Characteristic Magnetization Curves. B= flux density; H = magnetic field strength.

It is a well-known concept that the presence of mechanical strain and changes in microstructure will affect the magnetic permeability of ferrous materials; this is called the inverse magnetostrictive effect or the Villari effect. However, the degree of the effect will depend on a number of factors such as the material composition, magnitude and variation of stress, material geometry, variation in microstructure, magnetization direction, and so on. It can be assumed that the heavily deforming prestressing force in the strands will definitely affect their magnetic properties. Even though there have been previous attempts to determine the magnetic hysteresis loop of different materials, because of the sensitivity of the magnetic properties to the geometry and material composition, the hysteresis loops of any steel material may not be simply substituted. Thus, the only reliable way to understand a material is to find the hysteresis loop of the target construction materials (Devine, 1992; Jiles and Atherton, 1984).

Initial Concept

An initial concept was to fabricate roughly a device with two neodymium iron boron rare earth permanent magnets as the source of the magnetic field to inspect prestressing strands, typically 2 in below the surface of prestressed concrete box beams. The magnets were placed at the ends of a permeable pole piece to concentrate and direct the magnetic flux toward the beam. The device would be placed on the surface of the beam and positioned over a strand. In addition to the magnets, the device would include an array of Hall effect sensors to measure leakage flux, internal electronics to acquire and process signals and to interface with a laptop computer via a USB port.

A two-dimensional (2D) finite element model was used to simulate the operation of this conceptual MFL device. As shown in Figure 2, for an intact strand, the magnetic flux from the permanent magnets is strong enough to saturate the strand, and there is very little MFL.

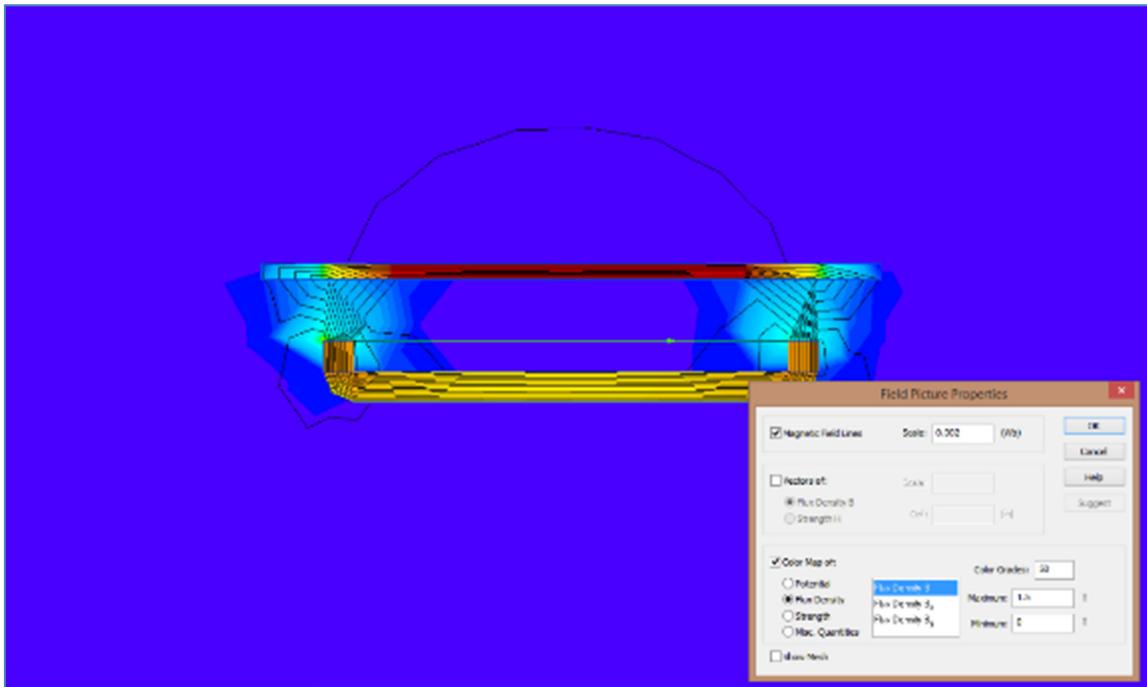


Figure 2. Finite Element Simulation of an Intact Strand

The magnetic flux density in both the x and y directions will be measured close to the surface of the concrete by an array of Hall effect sensors. These sensors are quite sensitive and able to provide an analog voltage proportional to the magnitude and polarity of these fluxes. The B_x (the flux density aligned in the direction of the strand) and the B_y (the flux density perpendicular to the strand) will be measured. The variation in the values of these fluxes from the 2D simulation for an intact strand is shown in the y-axis in Figure 3, along the length of the strand represented by the x-axis, where the two magnets were placed 12 in apart, equidistant from the origin.

For a broken strand, there is very significant flux leakage, as shown in Figure 4. Similar to Figure 3, the flux values for a broken strand, which would be measured by the Hall effect sensors, are shown in Figure 5.

There is a characteristic increase in the magnitude of the flux in the y direction with a much lower change in the x direction. The location where the polarity of B_y changes is related to the relative location of the break with respect to the sensor array.

A strand with some loss of section but not yet broken will present indications that are intermediate between the two extremes described. A simulation was performed for a strand with a 40% section loss. The results are shown in Figures 6 and 7.

It would be advantageous for a MFL device to have a self-containing, user-friendly interface, which would eliminate the need for a computer during routine inspections. By coupling the individual Hall effect sensor modules with a color-coded bar display, a characteristic pattern could be presented when the MFL device is positioned directly over a broken strand. This would require further design, but the concept is illustrated in Figure 8.

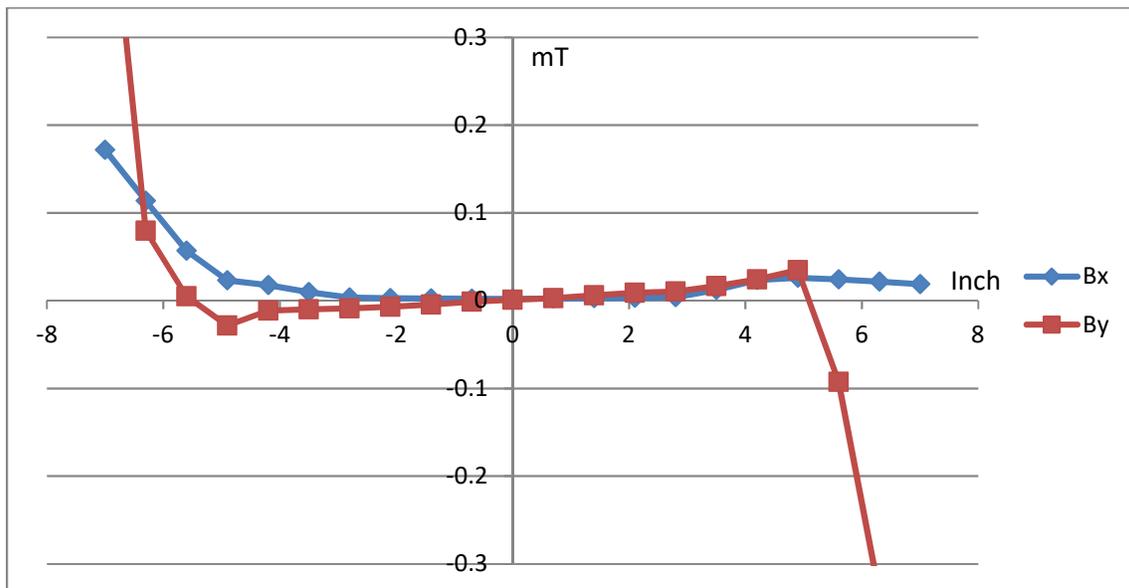


Figure 3. Longitudinal and Transverse Flux Density (mT) Along Length (in) of Intact Strand

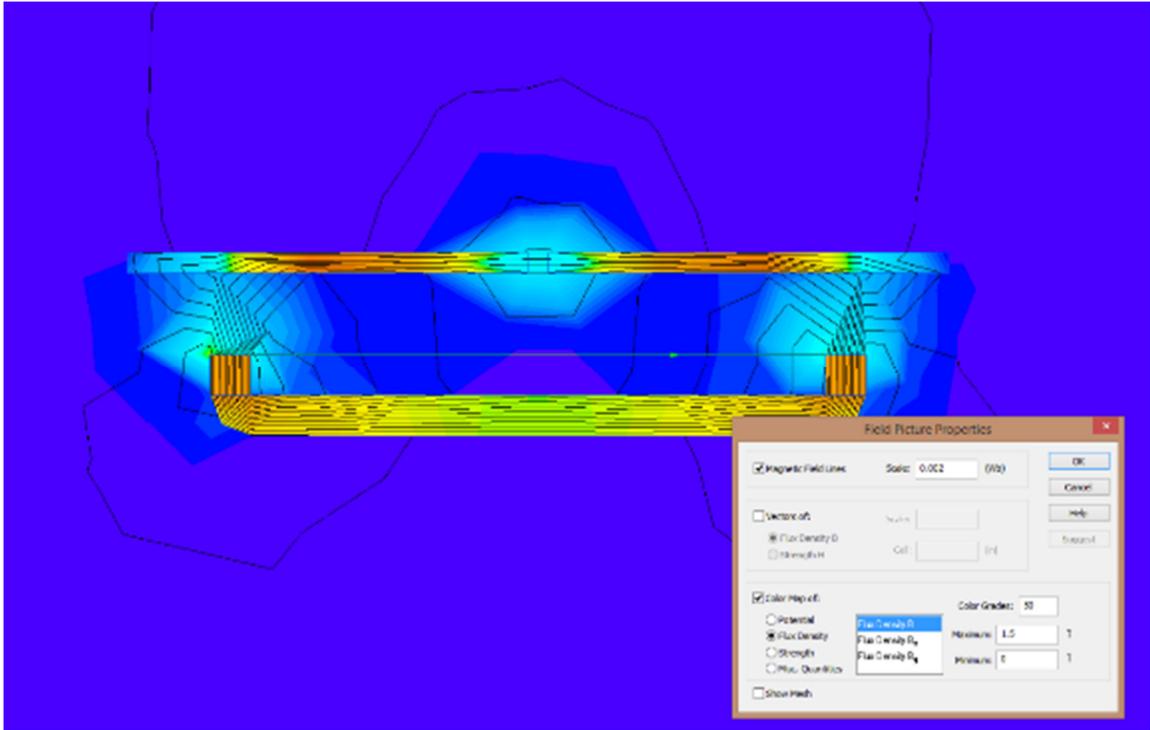


Figure 4. Flux Density for a Broken Strand

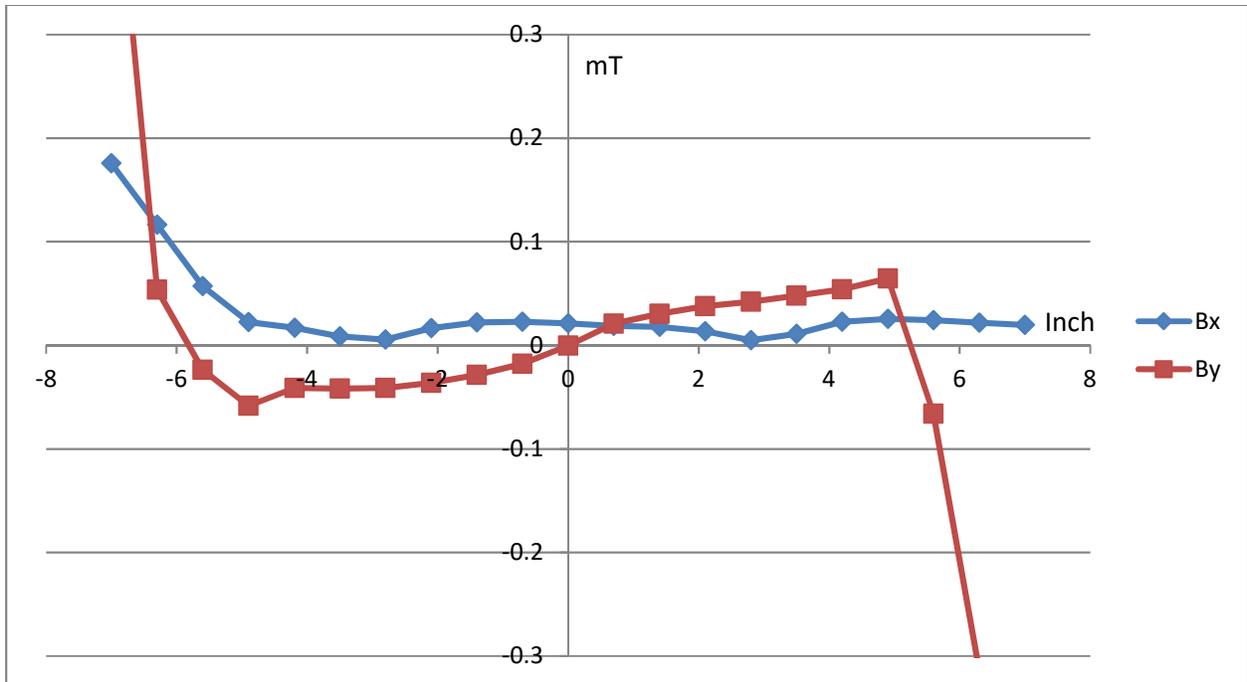


Figure 5. Longitudinal and Transverse Flux Density (mT) Along Length (in) of Broken Strand

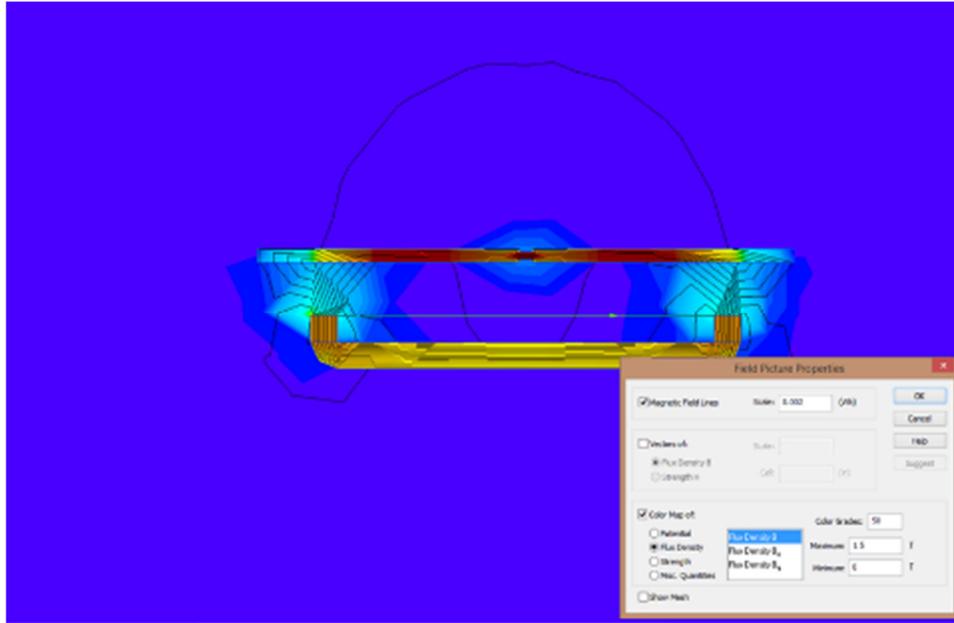


Figure 6. Flux Density for Strand With 40% Section Loss

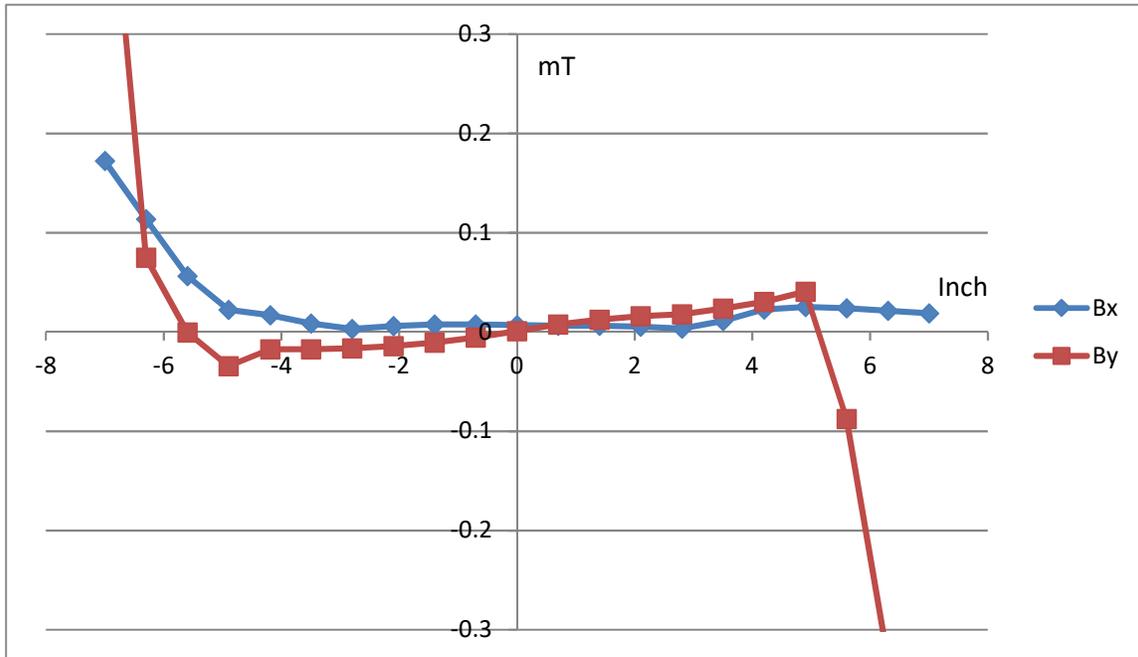


Figure 7. Longitudinal and Transverse Flux Densities (mT) Along Length (in) for 40% Section Loss

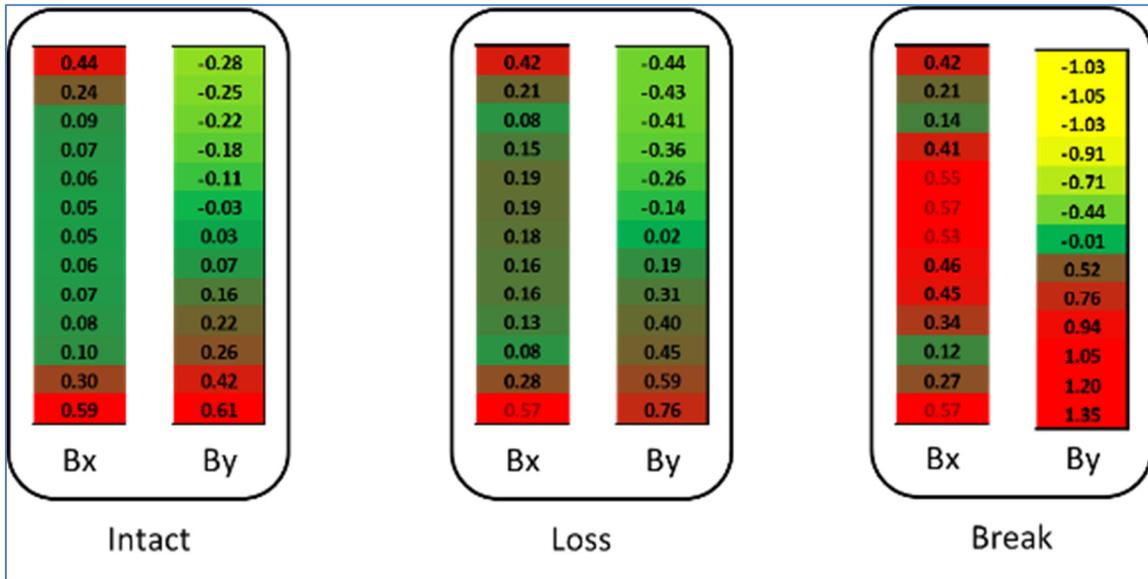


Figure 8. Conceptual Test Indication of Magnetic Flux Densities (mT)

Such a display would provide an indication to the inspector, which would be very easy to interpret. The device would also have the capability of interfacing with a laptop computer for more accurate and quantitative scanning to follow up on such indications.

PURPOSE AND SCOPE

The purpose of this study was to design and deliver a pilot version of a prototype inspection tool for inspecting prestressing strands in prestressed adjacent box beams based on the MFL method.

The scope was limited to prestressing strands with a concrete cover of up to 2 in. The study included conceptual design and finite element model simulation and parametric studies. Laboratory tests and validation of the model results on a mockup of a prestressed concrete beam were conducted. The scope also included a verification of the field usage of the prototype.

METHODS

The methods used to perform this study consisted of a series of tasks, each of which built on the results of the previous task.

1. Conduct computer simulations of variables related to the magnetic flux intensity, distance between magnets, and degree of damages in the prestressing strands.
2. Perform laboratory testing on a mockup of a prestressed box beam to observe the responses from the strands.
3. Test an MFL prototype device to inspect strand section losses.

Task 1: Computer Simulations

Beginning with the initial conceptual design described previously, a number of more refined 2D finite element simulations were performed. The results of these simulations guided the design of the experimental portion of the study.

Task 2: Laboratory Tests

Test Fixture

A test fixture was designed and implemented to simulate a typical prestressed box beam. The test fixture consisted of a plywood box 2 ft wide, 4 ft long, and 1 ft deep. A layer of ½-in-diameter prestressing strands, spaced at 2 in, was placed so that the distance from the top of the fixture to the top of the strands was 2 in. The strands could be removed and adjusted in the fixture. One of the strands was intentionally damaged in such a way as to allow replicate damage scenarios ranging from an intact strand to a strand with six fully broken wires.

In addition to this mockup of a box beam, an x-y scanner was designed and fabricated, which enabled programmable 2D movement of a magnetic field sensor, using a 2D x-y plotter purchased for this purpose. In addition, a power supply, stepper motor controllers, and a microcontroller were purchased and integrated into a complete scanning system.

A magnetic field sensor was also integrated into the test fixture. Several magnetic sensors were evaluated, and the TLV493D 3-axis magnetic field sensor was selected for this test fixture. This sensor provided the ability to measure the three components of the magnetic field with high precision and accuracy.

Images of the test fixture are provided in Figures 9 and 10.



Figure 9. Magnetic Flux Leakage Inspection System Test Fixture

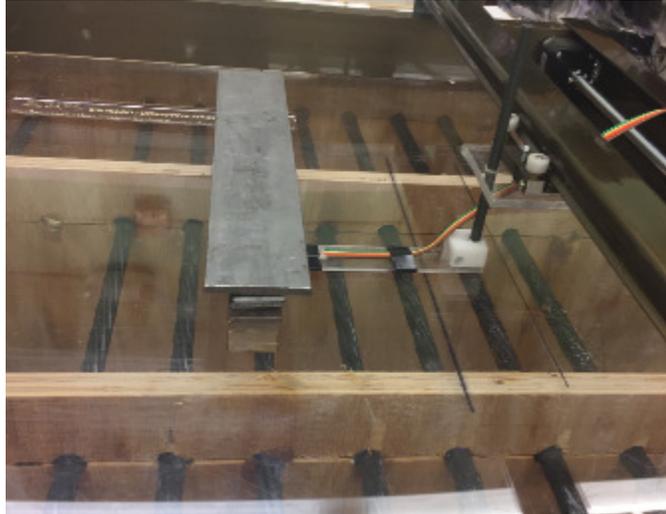


Figure 10. Magnetic Sensor and Magnets

The tests performed with the test fixture measured the three-dimensional (3D) magnetic field at a resolution of approximately 0.1 in. Measurements were performed for seven damage scenarios. The scenarios ranged from intact strand to strand with six fully broken wires. The helical nature of the wires in a typical seven-wire strand enabled the same strand to be used to produce all seven of the damage scenarios. An image of strand with two broken wires is provided in Figure 11. The tapered ends of the damaged wires are intentional. Previous studies have used sharply cut wires, and this abrupt change in metal cross section induces large flux variations. Observation of damaged strands from decommissioned bridges showed that a more gradual loss of metal, because of corrosion, is more typical.



Figure 11. Strand With Gradual Section Loss

The portion of the strand with the damage was centered between two magnets in the test fixture, and the magnetic field between the magnets was measured by scanning the sensor in a rectangular grid and storing the measurements as a text file on a laptop computer. The position of the sensor was also recorded to enable detailed post-processing of the collected data.

The tests on each of the damaged strands were repeated at least 3 times to ensure representative results.

Task 3: Prototype Design and Implementation

The prototype was built with two high-strength magnets mounted on a steel pole piece, a series of Hall effect sensors, a microcontroller module, and multicolor LED lights. The pole piece also served as a suitable support for the handle and a place to attach the housing. The housing was fabricated from non-magnetic materials (wood and aluminum). The magnets were positioned with about 6 in between the inside faces. The electronics consisted of a microcontroller module, a Hall effect sensor array module, and a multicolor LED array unit.

The microcontroller module was an Arduino Mega 2560 and was programmed in C language to interface with the sensors and to provide indications of the results by causing the multicolor LEDs to be illuminated from green to red, depending on the test results. The code is provided in the Appendix.

The prototype was fabricated in an upper and lower unit. The upper unit provides the main structural support and contains the magnets, the pole piece, a handle, and Velcro supports for the multicolor LED array. The lower unit consists of a wooden frame and the electronics. The electronics include the microcontroller module, the Hall effect sensor array module, and the multicolor LED indicator array. The unit is shown in Figures 12 and 13.

The microcontroller is powered by a USB cable. This same cable is used to program the microcontroller and to communicate with a laptop if desired.

The device is easily operated. Once power is supplied, the microcontroller initializes the system, and when it is ready to begin taking measurements, all five of the multicolor LEDs will be green. The device is then placed on the surface of the box beam to be inspected. There might be a momentary change in indication as the magnetic field changes as the device is positioned. Once all five LEDs are green, the device is moved along the surface at a steady rate of 2 to 3 in per second. The device samples the magnetic field between the magnets twice every second and responds to abrupt changes in the magnetic field. As discussed later, the presence of section loss (corrosion damage) results in an abrupt and measurable difference in the flux over a short distance. If the flux change exceeds a threshold value, the color of the LED changes from green to yellow to red, depending on the magnitude of the flux difference.



Figure 12. Disassembled MFLIS Prototype Device. MFLIS = magnetic flux leakage inspection system.

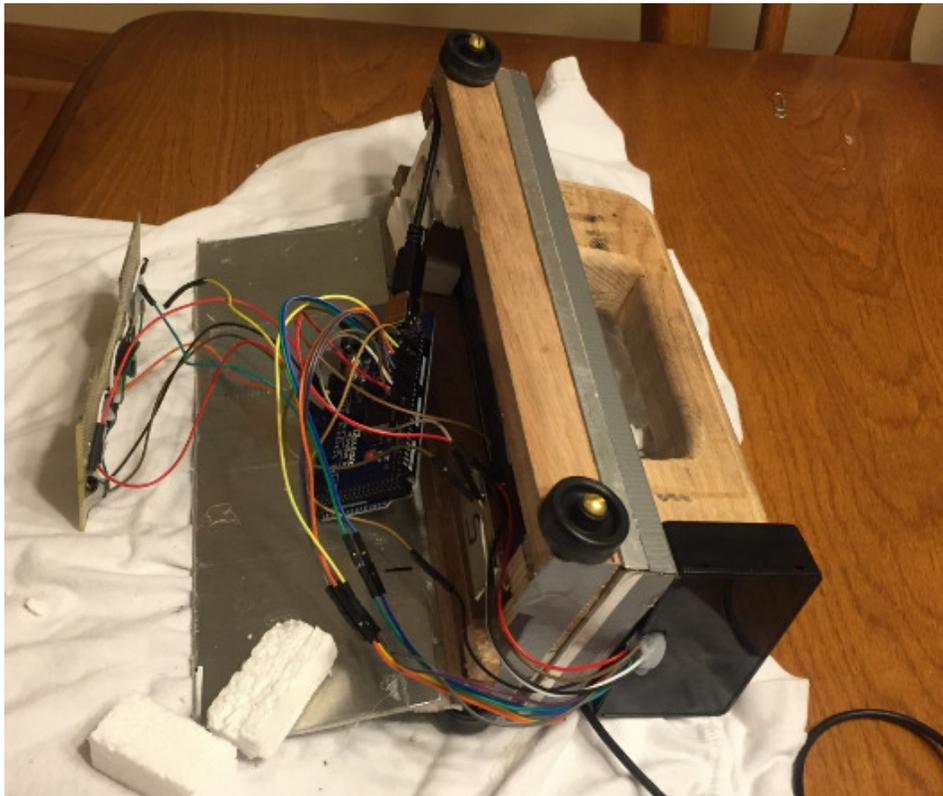


Figure 13. Assembled MFLIS Device Before Bottom Cover Is Closed. MFLIS = magnetic flux leakage inspection system.

Laboratory Testing of Prototype

The prototype device was tested in the laboratory using the same mockup box beam used for the preliminary tests. No laboratory testing was conducted using strands embedded in concrete because concrete often has negligible magnetic resistance unless iron-bearing aggregates were used. Since the concentration of iron and percentage of iron-bearing aggregates in the concrete can affect the magnetic properties of the concrete itself and since this resistance can vary widely, this parameter was not taken into account in this stage of the study. This parameter should be tested separately once the effectiveness of the MFL device has been identified.

The prototype was moved over intact and damaged strands to record the results, as shown in Figure 14.

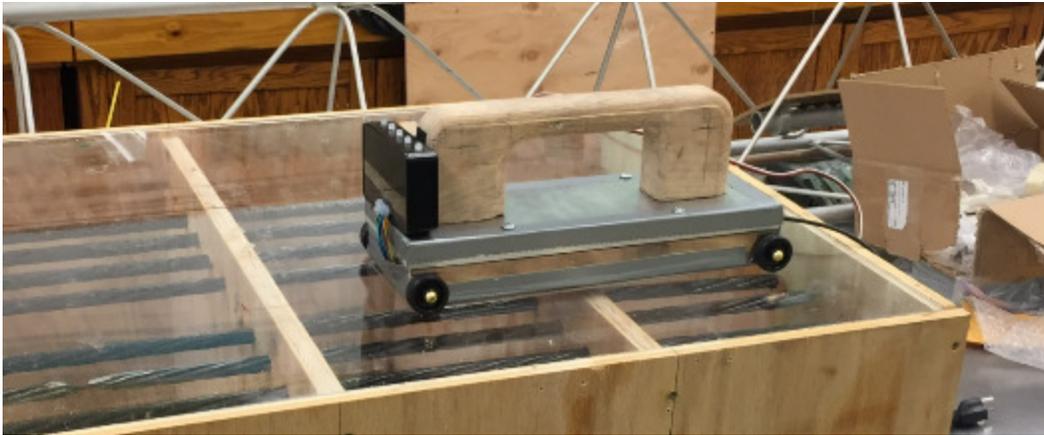


Figure 14. Prototype Tested on Mockup

Field Trial

There are specific problems that are associated with the field implementation of a technology, so to identify any preliminary field-specific problems, the MFL prototype was used to evaluate a prestressed box beam bridge with known inspection data.

RESULTS AND DISCUSSION

Task 1: Computer Simulations

Many simulations were performed using ANSYS 19.0 finite element software by ANSYS, Inc. Simulations were performed for different magnets with various strengths and for different damage scenarios. The responses in the magnetic flux for different degrees of damage in the prestressing strands are shown in Figures 15 through 17. The MFL that occurs between the strand and the magnets will be captured using Hall effect sensors, as initially shown as simplified plots in Figures 3, 5, and 7.

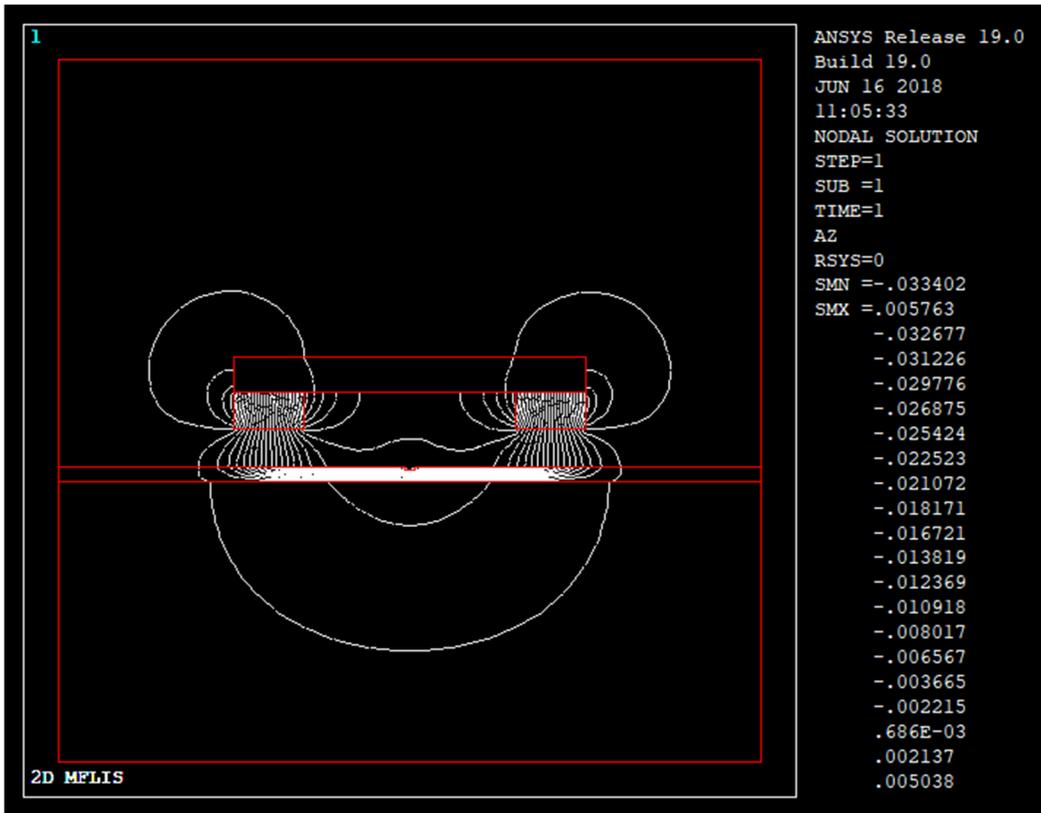


Figure 15. Flux Density Simulation With 10% Section Loss

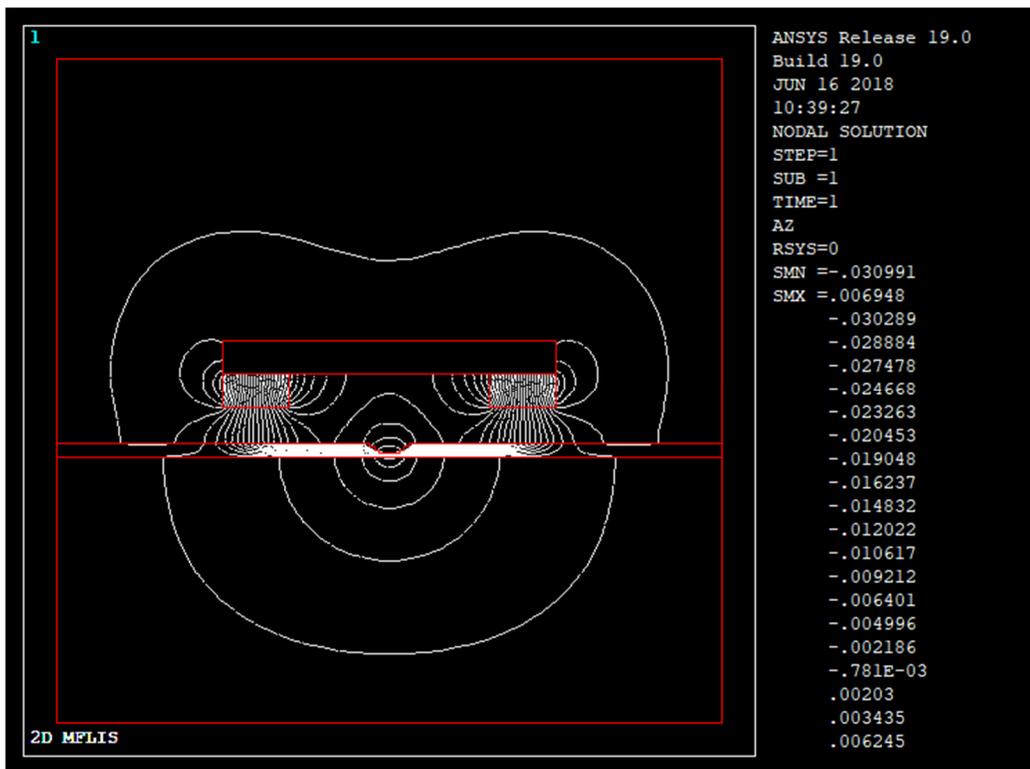


Figure 16. Flux Density With 75% Damage

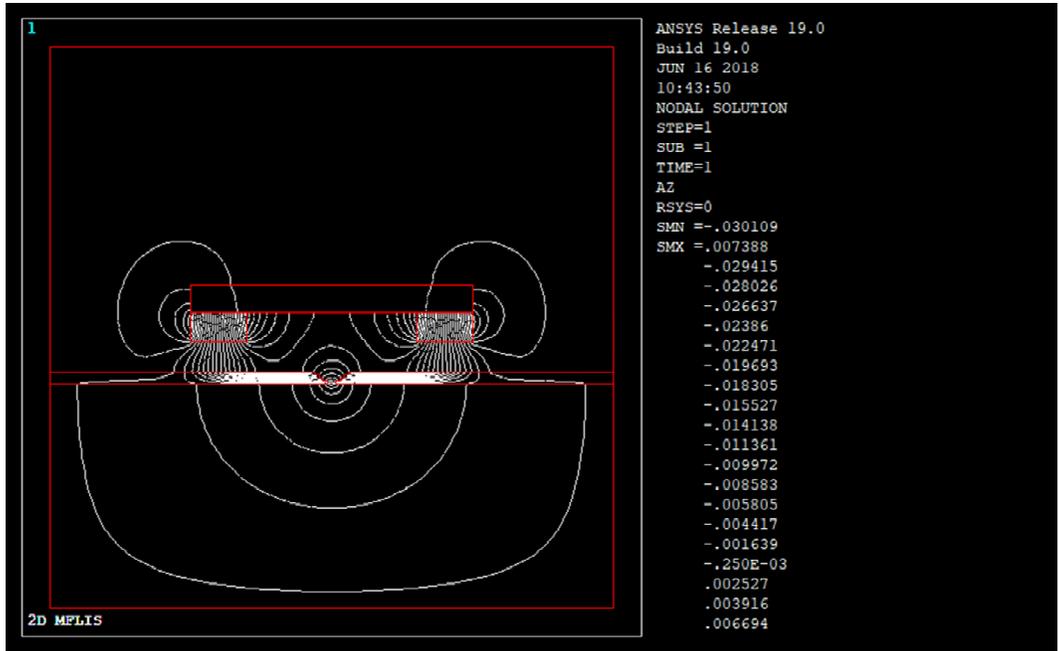


Figure 17. Flux Density With 100% Damage

It was observed that the flux leakage varied along the interval between the interior faces of the magnets. The transverse flux density in this interval was plotted for all of the different damage scenarios, and the results are shown in Figure 18.

The simulations indicated that there was a significant difference between the flux density profiles between the magnet faces. The differences in flux density values were also within the range of values that can reliably be measured with the available sensors. The results also suggest that the slope of the flux density profile near the center of the device might be a useful damage indicator.

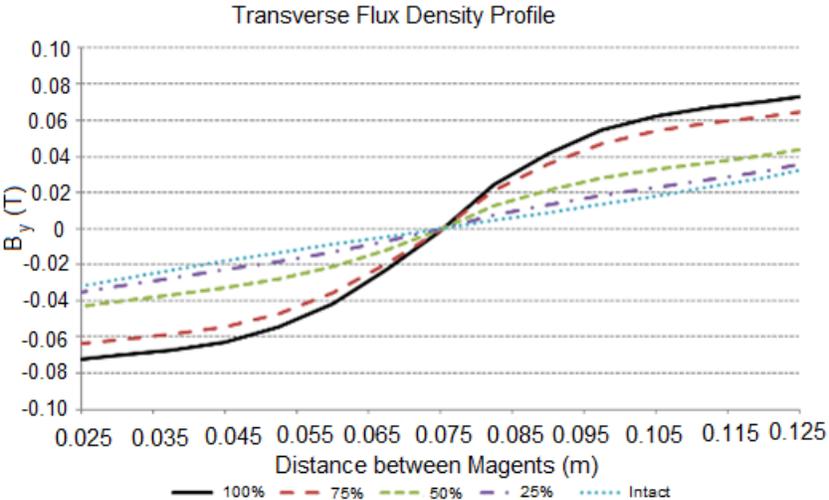


Figure 18. Flux Density Profile Between Magnet Faces for Percentages of Section Losses

Task 2: Laboratory Tests

The laboratory test results provide measured 3D flux density field values for different damage scenarios. The sensor used provided flux density values in three mutually perpendicular directions. It was originally hypothesized that the additional data from all three axes would help detect damage by revealing previously unknown patterns in the flux density values in the presence of damage. However, it was found that the additional data did not reveal any useful patterns and that the transverse flux density profile was adequate to characterize the changes in flux density associated with damage. It was also noted that the profile of the transverse flux density had a maximum value between the magnets aligned with the maximum flux gradient. This is illustrated in Figure 19 for intact strand and in Figure 20 for a strand with six broken wires. The x-axis represents the distance between the two magnets.

The maximum flux density profile for the different damage scenarios were determined, as shown in Figure 21. Only the negative segment of the curves are plotted in order to help show the differences between the curves. There is a slight offset along the x-axis in the curves because of slight differences in the initial position and the location of the damaged portion of the strand. The different tests required manual placement of the strand, and slight differences in the relative position of the damaged portion of the strand relative to the center of the test magnets are expected.

The maximum measured difference in flux density between an intact strand and a strand with six broken wires at position 50 was 0.28 mT. This was less than predicted by the finite element simulation, but it is still measurable with the Hall effect sensors used in the device.

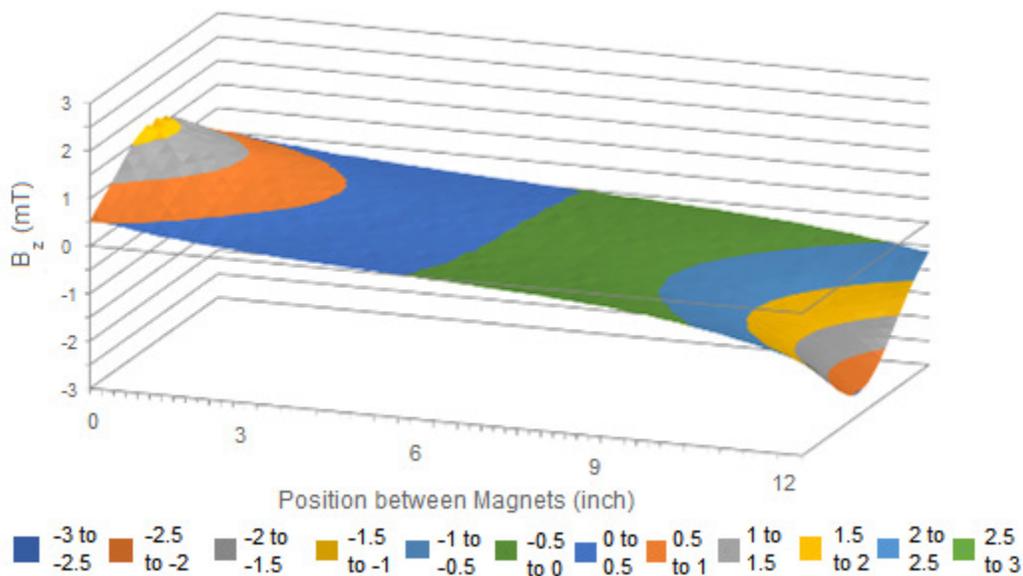


Figure 19. 3D Flux Density Field for Intact Strand

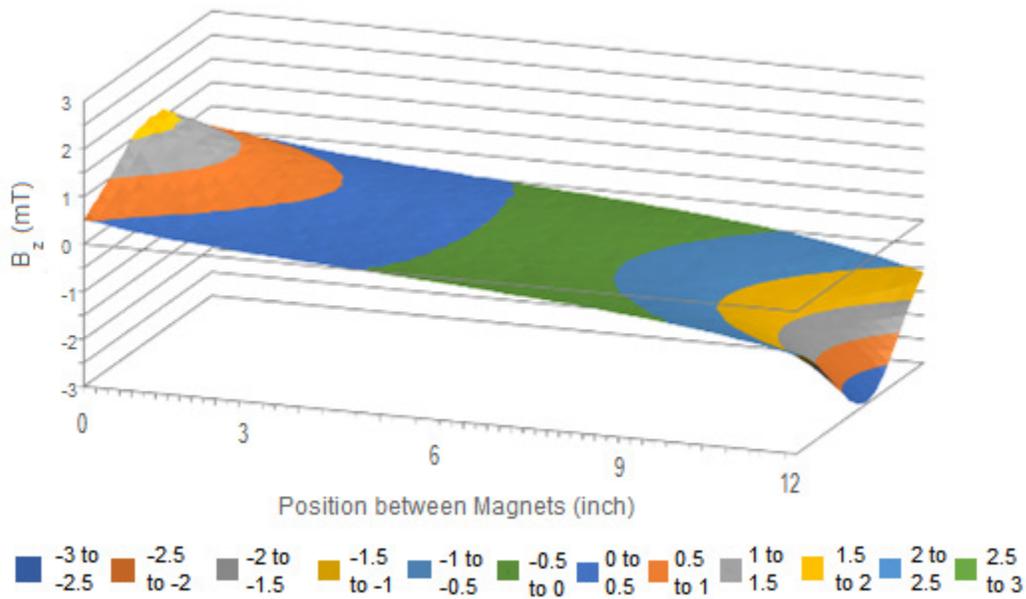


Figure 20. 3D Flux Density Field for Strand With Six Broken Wires

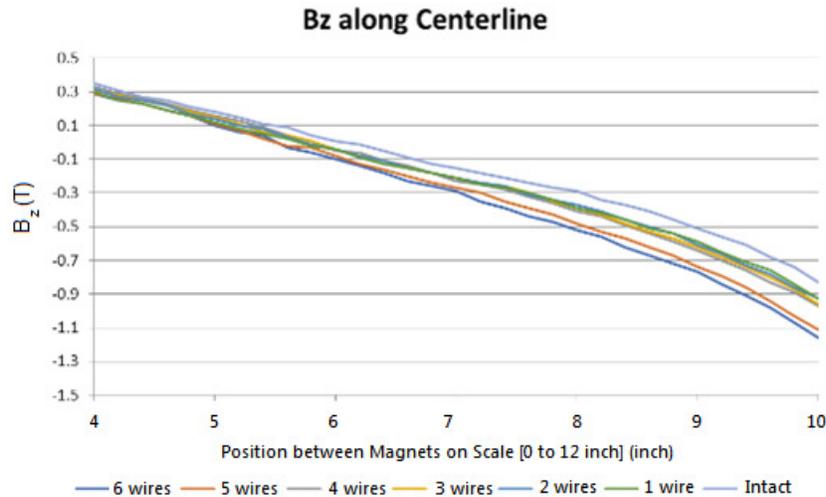


Figure 21. Profile of Measured Maximum Transverse Flux Density for Different Damage Scenarios

Prestress and Magnetic Permeability

Magnetic properties of materials reduce with the presence of mechanical stress. The prestressed strands carry enormous mechanical stresses and thus will have different magnetic properties compared to unstressed strands. This will affect the results of MFL testing. Thus, a laboratory test of the effect of mechanical stress on the magnetic permeability of the strands was conducted, as shown in Figure 22.



Figure 22. Tensile Loading and Magnetic Permeability Measurement

A solenoid was placed around the strand during load testing to measure the inductance in the coil. Equation 1 shows the relationship between inductance in the solenoid coil and the magnetic permeability of the strand.

$$L = \frac{N^2 \mu A}{l} \quad [\text{Eq. 1}]$$

where

L = inductance of coil

N = number of turns in the coil

μ = permeability of core material (strand)

A = area of coil

l = length of coil.

A Grade 250 strand and a Grade 270 strand were tested in this manner. The results are shown in Figures 23 and 24, respectively. The inductance started around 32.5 mH for both strands. When the strands were loaded gradually, the inductance increased, but with different magnitudes for the two strands, as indicated by the blue line. However, the shapes of the hysteresis loops were the same for both strands.

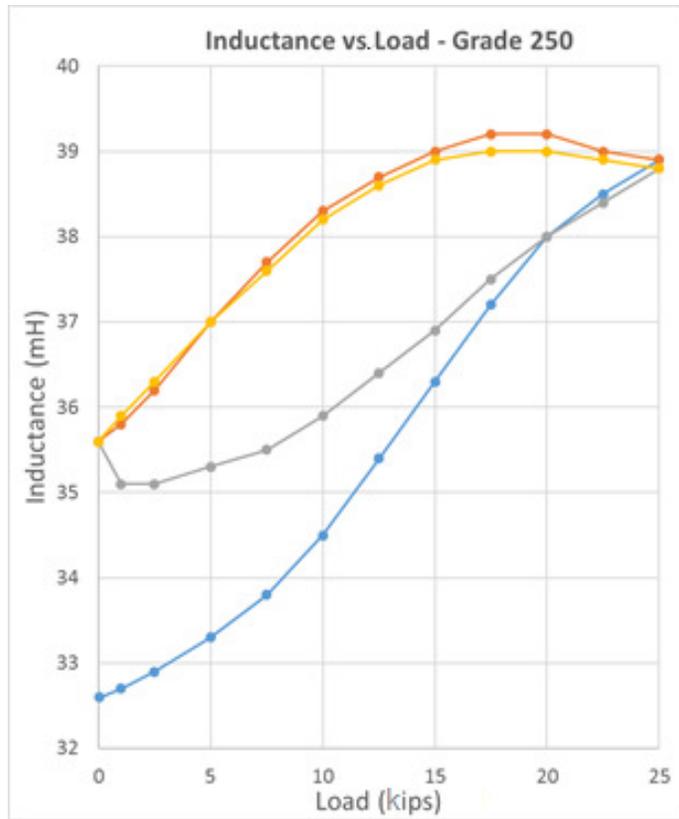


Figure 23. Stress and Magnetic Permeability of Grade 250 Strand

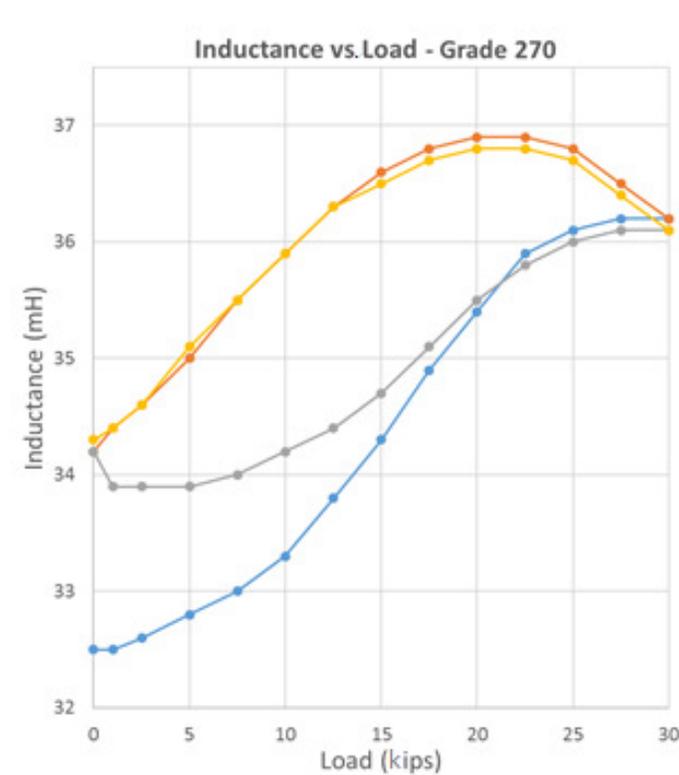


Figure 24. Stress and Magnetic Permeability of Grade 270 Strand

When loads reached 70% of the guaranteed ultimate tensile strength, the strands were gradually unloaded until there were no loads. It was observed that the inductance had permanently changed to a higher value, as shown by the difference between the starting point of the blue line on the left and the gray line. This is because of the change in the molecular structure of the strands caused by mechanical loading. When the strands were loaded and unloaded again, the inductance reached the same maximum value and came back to the same higher-low values. This shows that once loaded, the magnetic permeability can entirely change. This indicates that the magnetic flux readings should be taken in relative terms for better interpretation.

Task 3: Prototype Testing

The prototype device was used to scan the strands in the laboratory mockup. Damaged and intact strands were tested. The prototype was connected to a laptop computer, the measurements from the Hall effect sensors were recorded, and any indications on the multicolor LEDs were observed. The flux values varied along the strand, even for the intact strand. This was unexpected, although it could be explained by residual stress in the strand because of uncoiling, for example. The researchers decided to use the localized change in the flux relative device position as a damage indicator. Gradual changes in flux because of gradual permeability changes were eliminated, but flux changes because of localized corrosion damage were retained. This is illustrated in Figures 25 and 26. The plots show lines of five different colors indicating the five Hall effect sensors as the device was moved across the length of the strand. Since the overall response at the Hall effect sensors was of interest and any specific reading from a Hall effect sensor was not useful for this technique, the colors were chosen arbitrarily.

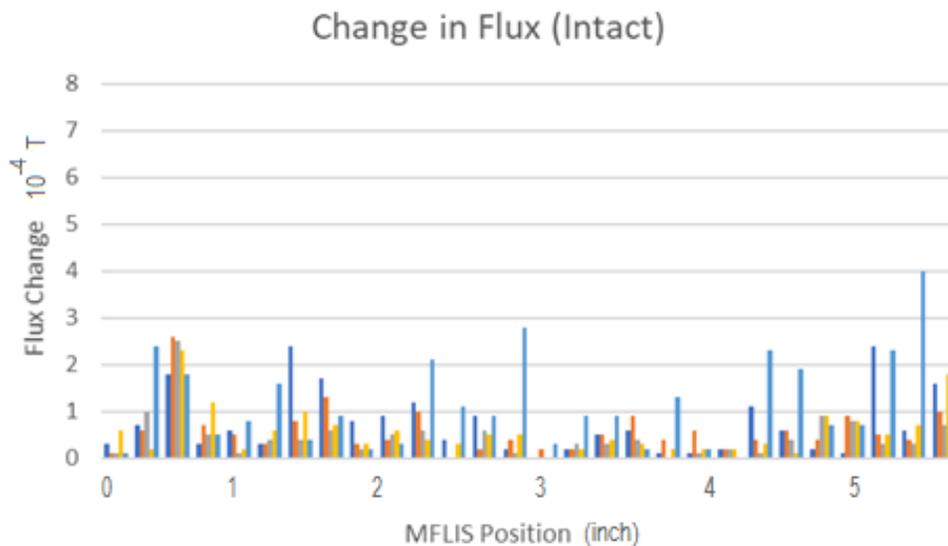


Figure 25. Localized Flux Change for Intact Strand. MFLIS = magnetic flux leakage inspection system.

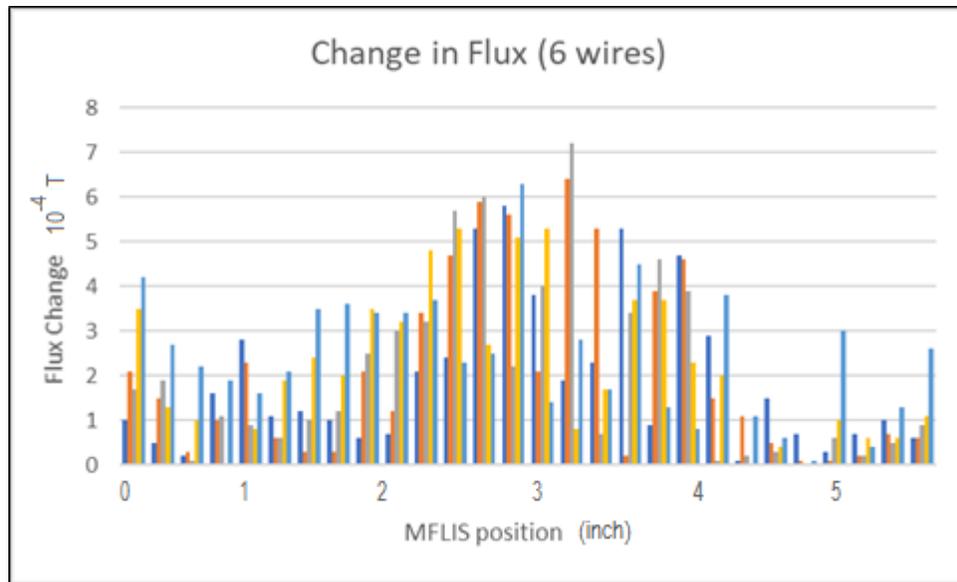


Figure 26. Localized Flux Change for a Strand With Six Broken Wires. MFLIS = magnetic flux leakage inspection system.

It can be noted that localized flux changes have much lower values for intact strand relative to damaged strand. It was possible to locate the damaged portion of the strand by observing when the localized flux change exceeded a threshold value. A threshold of 5×10^{-4} T was selected for the change in flux as the severe damage threshold value based on these laboratory tests.

Field Tests

The bridge on Rt. 601 over Mechums River in Albemarle County (Federal No. 631, State No. 6005), just outside Charlottesville, Virginia, was selected for the field tests. This bridge was constructed in 1981 and had been in service for 37 years when inspected. Routine inspection in 2017 showed that the superstructure had a general condition rating of 5 with about 10% of the beam length containing delaminations and spalls.

Testing consisted of applying the device to different box beams with apparent delaminations and solid sections and observing the results. The device is shown in the hand of an inspector in Figure 27. The green indications of the LED should be noted. The device was then used to scan the underside of a box beam as shown in Figures 28 and 29.

The results of the field tests are summarized as follows: It was demonstrated that the prototype device could differentiate between different damage severities and that a field-ready version of the device could be used during a typical routine bridge inspection by a single operator; however, this was not validated using cores. The prototype unit weighed less than 20 lb, but it was noted that extended use could be fatiguing. The device could produce indications in real time; with some improvements, the device could quantify the section losses. The device was powered by battery during the field test. Total battery life was not tested, but the battery packs can be easily swapped out within a few seconds.

Although not demonstrated during the field test, the laboratory test demonstrated the capability of the device to capture and record quantitative measurements, which could be recorded on a field computer.



Figure 27. MFLIS Device Being Used by Inspector. MFLIS = magnetic flux leakage inspection system.



Figure 28. MFLIS Device Scanning Underside of Box Beam. MFLIS = magnetic flux leakage inspection system.



Figure 29. MFLIS Device Showing Change in Flux. MFLIS = magnetic flux leakage inspection system.

CONCLUSIONS

- *This study demonstrated that available analytic tools and technologies can be used to solve a specific problem for infrastructure inspection. In this instance, the use of the well-established and mature MFL method was implemented in a low-cost and easily used device for the evaluation of the condition of hidden prestressing strand in box beams. The prototype delivered met all of the success criteria established at the beginning of the study.*
- *This study delivered a new tool to VDOT that can provide new capabilities for the inspection and evaluation of prestressed box beam elements.*
 - *The MFL technique can be qualitatively applied to detect section loss in prestressed strands. The prototype MFL device designed, fabricated, and tested in this study can provide useful information on the presence of defects in prestressing strand on box beam bridges.*
 - *The MFL technique can qualitatively indicate the severity of section loss in prestressed strands. The prototype device can provide information on the relative severity of localized strand damage.*
 - *The prestressing force in the strands affect their magnetic properties, but the level of change will not be significant enough to affect MFL results.*

RECOMMENDATIONS

1. *VTRC should propose a research needs statement and seek proposals for a follow-up study using implementation or other sources of funding to improve the MFL device in terms of analyzing and displaying results and fabricating a lighter, more portable, self-containing instrument for field deployment for inspecting bridges in service.*

IMPLEMENTATION AND BENEFITS

Implementation

Regarding Recommendation 1, an extension of the study could improve the field-implementable device to include better display of magnetic flux data and semi-automation to identify corroded areas of box beams. However, further improvement of this device in terms of analyzing and displaying results and fabricating a lighter, portable, self-containing instrument is beyond the scope of VTRC, in terms of resources. Therefore, the next step will be to develop a research needs statement and seek input and support for additional research at the fall 2020 meeting of the VTRC Bridge Research Advisory Committee.

Benefits

Regarding Recommendation 1, the prototype device can provide an indication of section losses in the prestressed strands in areas with shallow concrete cover. No off-the-shelf inspection equipment can provide this critical information on the condition of prestressed box beams, and this makes the outcome of this study highly significant for VDOT's infrastructure. The cost to reproduce the prototype system is well under \$1,000 per unit. Condition evaluation of the prestressing strands in the box beams prior to severe corrosion-induced damage will lead to informed decision-making regarding whether to repair, replace a single beam, or replace the entire superstructure. This will lead to improved safety of the traveling public, better performing box beam bridges, and cost savings to VDOT from making appropriate maintenance decisions.

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APPENDIX: COMPUTER CODE TO INTERACT WITH THE MFL TOOL AND SHOW RESULTS

```
// This code is used to program an Arduino Mega 2560 to interface with
// specially designed Hall effect sensors and multicolor LED indicators
// to implement a self-contained magnetic flux leakage device for the inspection
// of prestressing strands 2 inched below the surface of prestressed box beams.

// Define Pins

#define Green_1 3
#define Red_1 2
#define Green_2 5
#define Red_2 4
#define Green_3 7
#define Red_3 6
#define Green_4 9
#define Red_4 8
#define Green_5 11
#define Red_5 10

const int Hall_Sensor_1 = 0;
const int Hall_Sensor_2 = 1;
const int Hall_Sensor_3 = 2;
const int Hall_Sensor_4 = 3;
const int Hall_Sensor_5 = 4;

// define variables

int Init_Hall_Val_1 = 0;
int Init_Hall_Val_2 = 0;
int Init_Hall_Val_3 = 0;
int Init_Hall_Val_4 = 0;
int Init_Hall_Val_5 = 0;

int Hall_Val_1;
int Hall_Val_2;
int Hall_Val_3;
int Hall_Val_4;
int Hall_Val_5;

int Delta = 0;
```

```

void setup()
{
pinMode(Red_1, OUTPUT);
pinMode(Green_1, OUTPUT);
pinMode(Red_2, OUTPUT);
pinMode(Green_2,OUTPUT);
pinMode(Red_3, OUTPUT);
pinMode(Green_3, OUTPUT);
pinMode(Red_4, OUTPUT);
pinMode(Green_4,OUTPUT);
pinMode(Red_5, OUTPUT);
pinMode(Green_5,OUTPUT);

// Read Initial Hall Values
Init_Hall_Val_1 = analogRead(Hall_Sensor_1);
Init_Hall_Val_2 = analogRead(Hall_Sensor_2);
Init_Hall_Val_3 = analogRead(Hall_Sensor_3);
Init_Hall_Val_4 = analogRead(Hall_Sensor_4);
Init_Hall_Val_5 = analogRead(Hall_Sensor_5);

Serial.begin(9600);
}

// Define Functions

// the LED_Color function assigns one of three colores based
// upon the difference between the current hall value anf the previous hall value
// of the hall sensors. The sensitivity of the device is determined by the
// threshold values

int Led_Color(int Diff)
{
int result;
result = 0;
if (Diff >= 9)
{
result = 3; // Red
}
else if (Diff >= 4)
{
result = 2; // Yellow
}
else
{
result = 1; // Green
}
return result;
}

```

```
// the PWR functions are used to adjust the Pulse Width Modulation (PWM)
// for the red and green channels to create the three colors.
```

```
int PWR(int Color)
{
  int result1;
  result1 = 0;
  if (Color == 3)
    result1 = 255;
  else if (Color == 2)
    result1 = 175;
  else
    result1 = 0;
  return result1;
}
```

```
int PWG(int Color)
{
  int result2;
  result2 = 0;
  if (Color == 3)
    result2 = 0;
  else if (Color == 2)
    result2 = 50;
  else
    result2 = 255;
  return
  result2;
}
```

```
// main loop
void loop()
```

```
// Read magnetic flux density from Hall Array
// Use values to set colors for LEDs
```

```
{
  Hall_Val_1 = 0;
  Hall_Val_2 = 0;
  Hall_Val_3 = 0;
  Hall_Val_4 = 0;
  Hall_Val_5 = 0;
```

```
Hall_Val_1 = analogRead(Hall_Sensor_1);
Hall_Val_2 = analogRead(Hall_Sensor_2);
Hall_Val_3 = analogRead(Hall_Sensor_3);
Hall_Val_4 = analogRead(Hall_Sensor_4);
Hall_Val_5 = analogRead(Hall_Sensor_5);
```

```

Serial.print(Init_Hall_Val_1);
Serial.print("\t ");
Serial.print(Init_Hall_Val_2);
Serial.print("\t");
Serial.print(Init_Hall_Val_3);
Serial.print("\t");
Serial.print(Init_Hall_Val_4);
Serial.print("\t");
Serial.print(Init_Hall_Val_5);
Serial.print("\n");

Delta = 0;
Delta = abs(Init_Hall_Val_1 - Hall_Val_1);
Serial.print(Delta);
Serial.print("\t");
analogWrite(Red_1,PWR(Led_Color(Delta)));
analogWrite(Green_1,PWG(Led_Color(Delta)));
Init_Hall_Val_1 = Hall_Val_1;

Delta = 0;
Delta = abs(Init_Hall_Val_2 - Hall_Val_2);
Serial.print(Delta);
Serial.print("\t");
analogWrite(Red_2,PWR(Led_Color(Delta)));
analogWrite(Green_2,PWG(Led_Color(Delta)));
Init_Hall_Val_2 = Hall_Val_2;

Delta = 0;
Delta = abs(Init_Hall_Val_3 - Hall_Val_3);
Serial.print(Delta);
Serial.print("\t");
analogWrite(Red_3,PWR(Led_Color(Delta)));
analogWrite(Green_3,PWG(Led_Color(Delta)));
Init_Hall_Val_3 = Hall_Val_3;

Delta = 0;
Delta = abs(Init_Hall_Val_4 - Hall_Val_4);
Serial.print(Delta);
Serial.print("\t");
analogWrite(Red_4,PWR(Led_Color(Delta)));
analogWrite(Green_4,PWG(Led_Color(Delta)));
Init_Hall_Val_4 = Hall_Val_4;

```

```
Delta = 0;
Delta = abs(Init_Hall_Val_5 - Hall_Val_5);
Serial.print(Delta);
Serial.print("\n\n");
analogWrite(Red_5,PWR(Led_Color(Delta)));
analogWrite(Green_5,PWG(Led_Color(Delta)));
Init_Hall_Val_5 = Hall_Val_5;

delay(500); // determines sampling rate
}
```