Magnetic Sensor for Nondestructive Evaluation of Deteriorated Prestressing Strand

August 2011

Phase I Final Report

Principal Investigator:
Douglas K. Nims, Ph.D., P.E.
Associate Professor, Civil Engineering
The University of Toledo

Co-PI:
Vijay Devabhaktuni, Ph.D., P.Eng. (Alberta)
Associate Professor, Electrical Engineering and Computer Science
The University of Toledo

Prepared for
The University of Toledo University Transportation Center
Research and Tech Complex - R1
2801 W. Bancroft, Mail Stop 218,
Toledo, OH 43606-3390

Abstract

This is a report describing the activities and accomplishments in this project, completed through November 30, 2009. The overall goal of this project is to investigate the feasibility of a magnetic sensor to detect in-situ corrosion of prestressing strand in prestressed concrete bridge beams. Corrosion is a slow developing phenomenon which is not adequately detected using sensors currently in service. Despite national studies, no effective nondestructive sensor technology has been identified for prestressing strand corrosion. An effective sensor for corrosion will be able to get a snapshot of the corrosion in time by sensing the corrosion by-products or a direct change in member properties due to corrosion. This is a departure from the typical procedure of measuring a quantity, such as strain, which is a secondary effect of corrosion. The need for the proposed sensor is particularly acute in Ohio where there are many prestressed box girder bridges.

Experiments investigated the proposed method of magnetic detection for corrosion in prestressing strands. Two main clear findings are: 1) Magnetic detection can reliably distinguish cross sectional areas and 2) An improved electromagnet design would help in better and more practical detection. The first finding shows that development of a practical sensor can be undertaken with a reasonable prospect of success. The second finding shows that whether the remnant magnetism or the induced magnetic field method is used, it is necessary to achieve magnetic saturation of the samples at a higher level than what is possible with the small DC electromagnet used. A larger electromagnet which can reach a higher level of magnetic saturation and is designed for use with concrete will allow us to get an adequate signature of the remaining strand cross section. Achieving an effective magnetization through concrete requires an understanding of the magnetic properties of concrete and the magnetic fields for objects not in contact with the electromagnet. Based on the work to date, the fundamental difficulties that could be fatal to the sensor development are the need to magnetize the specimen from one side and the need to "see" through concrete. Access to a larger electromagnet designed specifically for this purpose can provide proof of concept resolution for these issues.

In addition, the research team has been successful in an initial interaction with a large industrial electromagnet firm, Ohio Magnetics, Inc., to develop a commercial partnership. Overall, the work has highlighted the need for a stronger electromagnet, motivation to strengthen the theoretical basis and has given the team confidence that the core idea of magnetic detection of the prestressing strand area is sound. The design and procurement of an improved electromagnet through Ohio Magnetics has already begun and will be used in the next phase.

Keywords

Concrete bridge, corrosion, deterioration, flaw detection, inspection equipment, magnetic, maintenance, prestressed concrete, reinforcing steel

Subject Categories

Maintenance, Bridges, Structures, Highways, Materials.

Contents

1. Introduction

The overall objective of this project is to develop a prototype magnetic sensor that can reliably estimate the remaining cross sectional area of exposed or hidden corroded prestressing strands in a laboratory setting. Critical strides were made in understanding the concepts of magnetization and developing a background in the theoretical understanding of electromagnetism. The team has also been successful in obtaining a proof-of-concept for steel rods of small diameters (0.2 in).

2. The Problem Addressed in the Project

The goal of this project has been to develop an electromagnet which will act as a sensor to determine the remaining effective cross-sectional area in corroded prestressing strand in concrete bridges. An accurate and convenient nondestructive inspection technique for detecting in-situ corrosion of prestressing strand, particularly in box beam bridges, will improve safety for the traveling public and assist in better maintenance planning.

Visual inspection is the method currently used to detect corrosion in prestressing strands in box beam bridges. Visual inspection is not adequate even when it is known a priori that the structure has extensive deteriorated strand (Abi Shdid 2006, Ferroni 2007, ODOT 2008, Scott 2006).

Unexpected failure of prestressed concrete box beam bridges due to prestressing strand corrosion has occurred. To determine the remaining flexural capacity of a prestressed bridge, the engineer must know the effective cross sectional area of the strand. The corrosion of the exposed strands is manifest, but their effective area must be estimated. The state of the strands where there is no spalling is unknown. It is desirable to be able to estimate the effective area of these strands without removing their cover. National studies have identified the development of an effective nondestructive sensor technology (FHWA 2010) as a research priority. Approximately 10% of the square footage of Ohio's bridges is box-girders, susceptible to prestressing strand corrosion (ODOT 2008).

3. Project Approach

This project is a step on the road to the development of a practical sensor for in situ estimation of the cross sectional area of corroded prestressing strands. The sensor, which is being developed, has the potential to spawn a product line and revolutionize inspection. Development of a magnetic sensor would be a fundamental breakthrough and there would be follow-up research on implementation. Additionally, an entire realm of research for in situ monitoring of the progress of corrosion would open up.

3.1 The Project Objectives

- Develop a prototype sensor based on magnetic principles and determine if it is promising enough to merit further development.
- Develop and execute a testing protocol to verify the sensor's ability to detect the cross sectional area of corroded prestressing strand in the laboratory. There will be a

progression of experiments examining the effect of gaps between the electromagnet and the specimen. This will culminate in the measurement of specimens embedded in concrete.
- Seek external funding to further the sensor development.

4. Literature Review

The project started by investigating the use of the remnant magnetic field method as proposed by Hillemeir and Scheel, 1997, 1998, who developed a sensor where prestressing tendons are magnetized with a yoke shaped electromagnet with up to 12 in. (300 mm) of concrete cover. They were successful in detecting fractures in prestressing wires. The idea derived from the work of Hillemeir and Scheel, is that the magnetic field induced in a ferromagnetic material is directly proportional to the cross section area of the specimen. The team's aim, as stated earlier, is to determine the sound or useful cross-sectional area in a corroded prestressing strand. Corrosion detection is important since fractures are developed as a consequence of corrosion.

In Scheel's Ph.D. dissertation, 1997, the basic concept of the remnant magnetic method is described. He has also shown through experiments using a yoke-shaped electromagnet that the magnetization of steel strands through concrete is possible. He, however, used it to detect fractures. The remnant magnetic method will be used in experiments conducted by the research team to obtain similar levels of magnetization.

Rumiche, et al., 2008, used a solenoid electromagnet which was toroidal in shape, to achieve magnetic saturation of specimens. Specimens were machined to simulate cross-sectional area loss. A linear relationship was found between the normalized mass loss and the magnetic saturation for all the sample specimens. However, the toroid cannot be used in a field application.

In Mihalache, et al., 2001, the magnetic flux leakage (MFL) method has been used to detect inner and outer defects in a steel plate. This is also a magnetization process using a yoke shaped electromagnet. A comparison between the experiment and simulated results was done for the remnant magnetic method as well as the continuous magnetization method. Both of these methods indicate that they are capable of detecting cracks in plates.

5. Technical Approach

Magnetic properties of steel are strongly affected by the corrosion. Rusting and corrosion introduce atoms of other elements (typically oxygen) into the material, thus changing the chemical forms of the material. Due to this change, steel becomes non-ferromagnetic or less ferromagnetic by orders of magnitude. By examining the magnetic characteristics of steel bars before and after corrosion, a correlation between the magnetic properties and remaining cross sectional area can be developed.

5.1 Methodology

In concrete structures, prestressing strand is embedded in concrete. In order to determine the cross-section area of the embedded strand they were magnetized externally using an electromagnet. A parallel-pole electromagnet as shown in Figure 1 was used to magnetize a steel rod specimen in air. For simplicity the experiment was carried out in air (without embedding in concrete) to prove the concept of magnetic induction being proportional to cross-section area. In doing so, the specimen was magnetized in proportion to its cross-sectional area. Thus, the magnitude of induced field gives a measure of the cross section area of the specimen. A Hall sensor is used to measure the magnetic field in the specimen. Comparisons of the magnetic field strength of non-corroded bar to corroded bar can be used to estimate the remaining cross-sectional area of the corroded bar. Conceptually, it can be argued that a yoke-shaped electromagnet with the specimen placed between the yoke legs, would be most suited to induce a magnetic field in the specimen. However, to test the concept put forward in this research it was decided to go forth using a parallel-pole electromagnet.

It was decided to carry out experiments with plain steel bars to start with, a Gaussmeter and a parallel pole electromagnet in the laboratory. The specimens would be of different diameters to compare the amounts of magnetic fields induced in them. This would help prove the concept that the induced magnetic field would be proportional to cross-section area of the specimen.

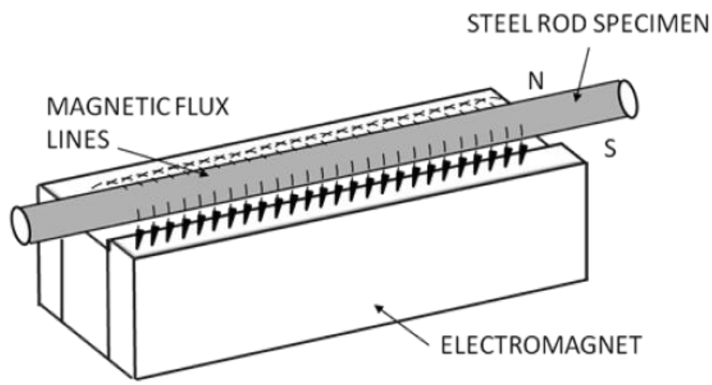

Figure 1. Magnetic field flux lines flow from north pole to south pole of the electromagnet through the rod transversely.

5.2 Equipment Used

A parallel pole DC electromagnet was chosen mainly due low budget available and ease of availability (no manufacturing wait time) from a local vendor at a very low cost. It can produce a magnetic field of up to 700 G at the center of each pole face. Its original use is as an industrial lifting electromagnet rated to lift loads up to 860 lbs. with full surface contact. The magnetic flux lines flow in a direction transverse to the length of the steel specimen under test, from the north pole to the south (see Figure 1.). In order to reuse the steel specimens, it would be necessary to get rid of any remaining magnetic field in it. For this, an AC electromagnet was used as a demagnetizer. The cost of the DC electromagnet along with the AC-DC power converter and demagnetizer was less than $1000.

The Gaussmeter was chosen based on sensitivity of the reading required for the magnetic field measurement. From Mihalache, et al., 2001; Scheel and Hillemeir, 1997; and Hillemeir and Scheel, 1998, the readings were found to be in the range of few Gauss to a few hundred Gauss, with the least count in the range of 5 to 10G. With these criteria under consideration a Lakeshore

Model 410 Gaussmeter was chosen (Lakeshore). It has a measurement range of ±20 kG, a least count of 0.1 G and comes with transverse and axial probes.

Steel samples were chosen for simplicity so that the magnetic strength of the parallel pole DC electromagnet would be enough to magnetize them. The samples were 6 to 8 in. long and 0.25 to 0.5 in. thick in diameter. Grades of steel used were AISI 1020 steel and some other grades. The test area and equipment can be seen in Figure 2.

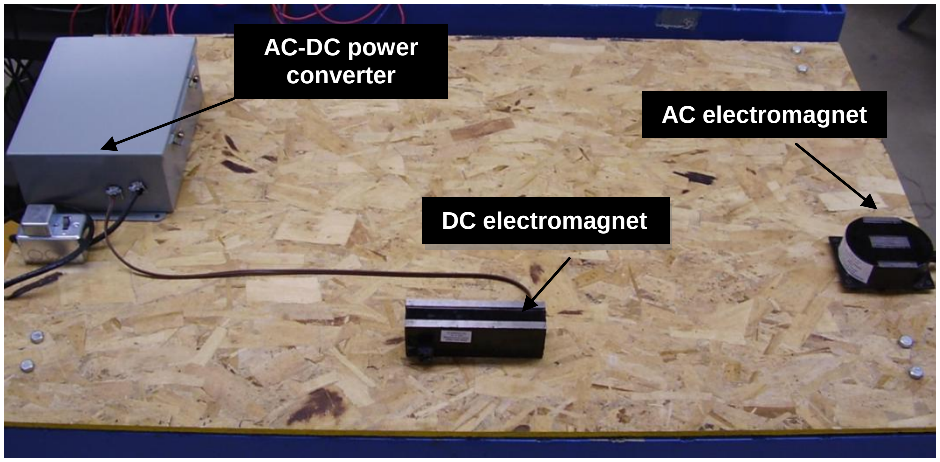

Figure 2. Setup for initial stage experiments.

6. Laboratory Experiments and Results

The laboratory experiments consisted mainly of magnetizing steel samples in the form of rods or rebar to measure the magnetic field induced in them. The main idea behind this was to obtain a relationship between the magnetic field induced in a steel sample and its cross-sectional area. It was decided to compare two measurement techniques: 1) measured magnetic field induced during the magnetization process; and 2) measure remnant magnetic field in the specimen after magnetization was complete. Initially, preliminary experiments were conducted by placing a specimen along the entire length of the electromagnet, magnetizing the specimen, and then measuring the remnant magnetic field. However, it was observed that the remnant magnetic field measured was not sufficient in magnitude to differentiate the cross-sectional area. This was most likely due to the fact that the electromagnet was not powerful enough to induce a magnetic field near or at the saturation point of the metal of the specimen. To overcome this problem, it was decided to directly measure the magnetic field induced in the specimen under the process of magnetization. Measurements were recorded at a distance of 5 in from the end of the electromagnet, where there is no influence of the magnetic field of the electromagnet detectable with the Gaussmeter. This set-up proved to be consistent and was used for the experimental trials.

A description of each experiment carried out using the electromagnet and other equipment described earlier is given below. An evaluation of the results obtained, problems faced and explanation of the reasons for further improvements for the electromagnet and other design and measurement parameters that need to be addressed are also explained. A detailed description of these experiments can be found in MS theses (Fernandes, 2010 and Wade, 2010). Successful experiments to detect cross-sectional area differences were conducted using the electromagnet and a Gaussmeter.

6.1 Experiment 1: To obtain a relationship between the induced magnetic field and cross-sectional area

The objective of this experiment was to establish a relationship between the induced magnetic field and the corresponding cross-sectional area of the steel rod specimen. This relationship will be used to compare results obtained in further experiments.

A specimen measuring 0.125 in. diameter, 6 in. length, cold-rolled AISI 1020 grade steel was placed on the electromagnet and allowed to overhang the electromagnet on one side by 5 in. This set-up can be seen in Figure 3. The readings are shown in Table 1.

Figure 3. Specimen position for trial 1.

Table 1. Magnetic flux density B [G], induced in steel specimen with diameter d [in.] for Trial 1.

Specimen #	d_1 (in.)	d_2 (in.)	d_3 (in.)	d_{avg} (in.)	Area (in^2)	B_1 (G)	B_2 (G)	B_3 (G)	B_{avg} (G)
1	0.1980	0.1935	0.1930	0.1948	0.0298	135	143	168	148.67
2	0.1980	0.1945	0.1940	0.1955	0.0300	142	159	150	150.33
3	0.1960	0.1965	0.1985	0.1970	0.0305	164	160	157	160.33
4	0.2175	0.2170	0.2190	0.2178	0.0372	175	185	183	181.00
5	0.2200	0.2200	0.2175	0.2192	0.0377	190	184	182	185.33

In the second trial, specimens were also de-magnetized between readings. The specimen was checked to make sure that there was negligible remnant field after demagnetization. The readings are shown in Table 2.

Table 2. Magnetic flux density B [G], induced in steel specimen with diameter d [in.] for Trial 2

Specimen #	d_1 (in.)	d_2 (in.)	d_3 (in.)	d_{avg} (in.)	Area (in^2)	B_1 (G)	B_2 (G)	B_3 (G)	B_{avg} (G)
1	0.1980	0.1935	0.1930	0.1948	0.0298	160	154	153	155.67
2	0.1980	0.1945	0.1940	0.1955	0.0300	157	157	160	158.00
3	0.1960	0.1965	0.1985	0.1970	0.0305	159	167	158	161.33
4	0.2175	0.2170	0.2190	0.2178	0.0372	180	191	191	187.33
5	0.2200	0.2200	0.2175	0.2192	0.0377	192	185	181	186.00

For the third trial, specimens were magnetized for 60 seconds before any readings were taken. In addition, no de-magnetization of specimens between readings was performed. The readings are shown in Table 3.

Table 3. Magnetic flux density B [G], induced in steel specimen with diameter d [in.] for Trial 3

Specimen #	d_1 (in.)	d_2 (in.)	d_3 (in.)	d_{avg} (in.)	Area (in^2)	B_1 (G)	B_2 (G)	B_3 (G)	B_{avg} (G)
1	0.1980	0.1935	0.1930	0.1948	0.0298	154	154	151	153.00
2	0.1980	0.1945	0.1940	0.1955	0.0300	153	155	154	154.00
3	0.1960	0.1965	0.1985	0.1970	0.0305	169	157	161	162.33
4	0.2175	0.2170	0.2190	0.2178	0.0372	180	181	184	181.67
5	0.2200	0.2200	0.2175	0.2192	0.0377	190	191	190	190.33

A review of the data collected from trials 1-3 showed that demagnetizing between readings was not needed. In addition, magnetizing for 60 seconds before taking a reading seemed to help stabilize the field and led to more consistent results. The graph of induced magnetic strength B [G] for the corresponding cross-sectional area A [in^2] of the specimen for the three trials described is shown in Figure 4.

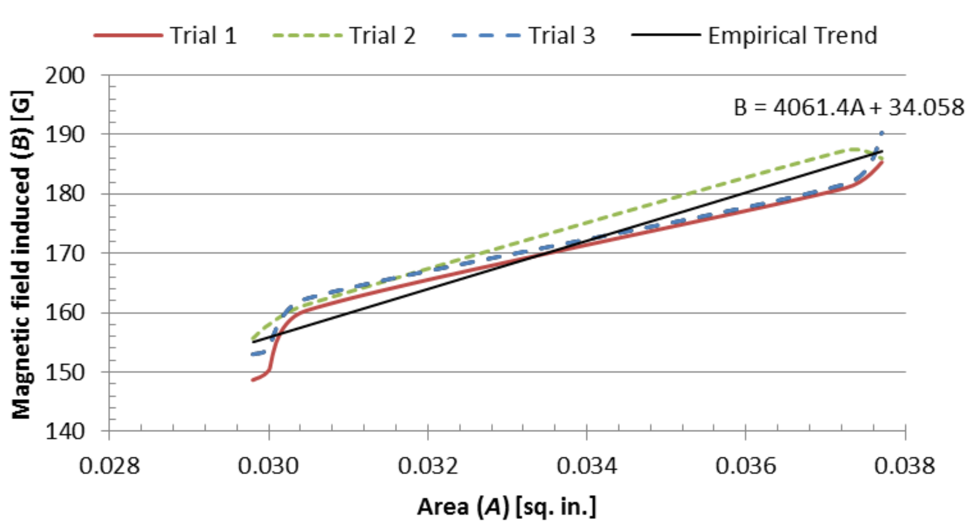

Figure 4. Comparison of trials 1-3 results in experiment 1.

From this graph, an empirical equation relating the induced magnetic field (B) and cross-sectional area (A) is obtained,

$$B = 4061.4A + 34.058 \quad (1)$$

which will be used to compare results obtained in the following experiments. The procedures for trial 3 were used for the remainder of the trials unless otherwise noted.

It was observed that magnitude of the induced magnetic field was insufficient to reliably ascertain the cross-sectional area of the steel rod. In order to repeatedly estimate the cross-sectional area accurately, the range of the measured field values needs to be larger and more spread out.

6.2 Experiment 2: Comparison of empirical and experimental values for different diameters of steel specimens

The purpose of this experiment is to use the linear fit equation (1) to calculate the field strength using the known value of cross-section area. The empirical strength value is then compared to the measured strength. By doing this the accuracy of the magnetic measurements can be studied. Specimens used were AISI 1020 steel (specimens 11-15) with diameters varying from 0.125 to 0.5 in.

Table 4. Magnetic flux density B [G], induced in steel specimen with diameter d [in.] for Trial 4

Specimen #	D (in)	Area (in^2)	Empirical B (G)	B_1 (G)	B_2 (G)	B_3 (G)	B_{avg} (G)
6	0.5	0.1963	831.11	270	263	260	264.33
7	0.375	0.1104	482.40	290	294	288	290.67
8	0.25	0.0491	233.32	230	236	227	231.00
9	0.1875	0.0276	146.14	189	187	184	186.67
10	0.125	0.0123	83.87	125	124	125	124.67

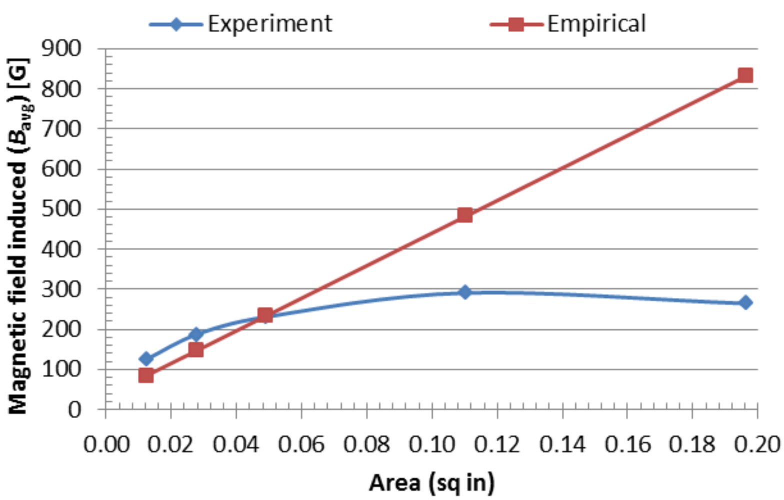

Figure 5. Induced magnetic field strength vs. cross-sectional for Trial 4.

Table 4 gives a comparison of the empirical and experiment values of induced magnetic field B [G] in trial 4. From the graph in Figure 5 it can be seen that the data shows a good match between the theoretical and experimental field strengths with the exception of specimens 6 and 7. This inconsistency is most likely due to the fact that the cross-sectional area of these specimens is too large for the electromagnet to completely magnetize and generate a good magnetic field and so does not magnetize it to near saturation.

Trial 5 was performed using specimens of 0.125 and 0.25 in diameter cold rolled steel. It was found that the magnetic field strength values are true for the equation for diameters up to 0.25 in. This can be seen in Figure 6. The data from trial 5 (in Table 5) shows a very good comparison between the empirical and experiment values except for specimen 12.

Table 5. Magnetic flux density B [G], induced in steel specimen with diameter d [in] for Trial 5.

Specimen #	d_1 (in)	d_2 (in)	d_3 (in)	d_{avg} (in)	Area (in^2)	Empirical B (G)	B_1 (G)	B_2 (G)	B_3 (G)	B_{avg} (G)
11	0.1920	0.1980	0.1950	0.1950	0.0298	155.29	159	157	160	158.67
12	0.2000	0.1970	0.2005	0.1992	0.0311	160.53	155	147	145	149.00
13	0.2190	0.2140	0.2190	0.2173	0.0371	184.65	181	182	182	181.67
14	0.2160	0.2180	0.2185	0.2175	0.0371	184.88	187	192	185	188.00
15	0.2175	0.2175	0.2215	0.2188	0.0376	186.73	191	187	186	188.00

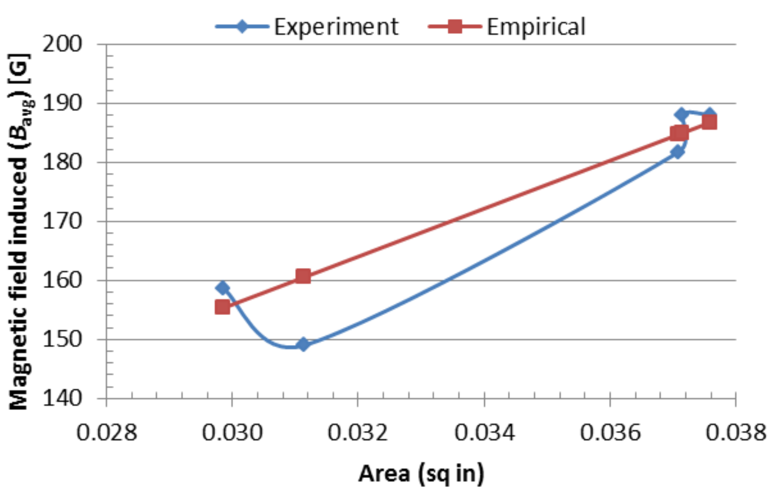

Figure 6. Induced magnetic field strength vs. cross-sectional area for Trial 5.

6.3 Experiment 3: Magnetization using an air gap

The next step in the experimental process was to put an air gap between the electromagnet and the specimen to simulate concrete cover. Trial 6 was the first trial done with an eighth of an inch air gap. The set-up for this trial can be seen in Figures 7 and 8. The data from trial 6 is recorded as Table 6.

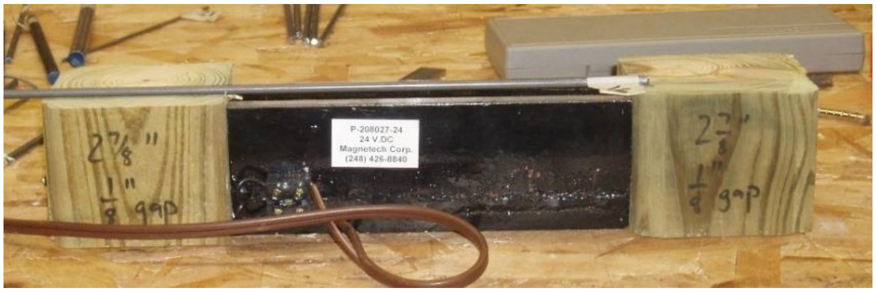

Figure 7. Trial 6 set-up.

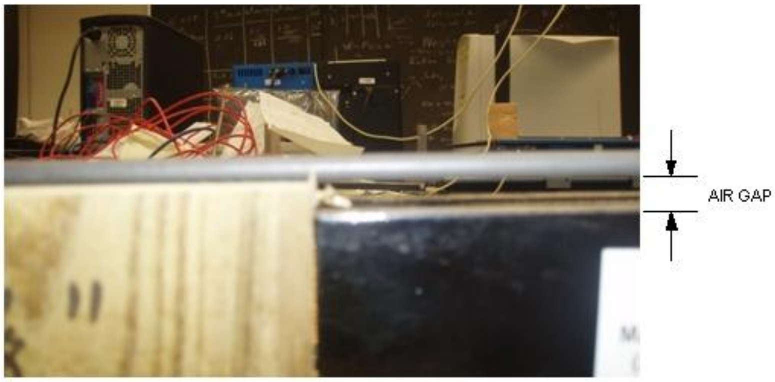

Figure 8. Close view of air gap for trial 6.

Table 6. Magnetic flux density B [G], induced in steel specimen with diameter d [in] for Trial 6.

Specimen #	d_1 (in)	d_2 (in)	d_3 (in)	d_{avg} (in)	Area (in^2)	B_1 (G)	B_2 (G)	B_3 (G)	B_{avg} (G)
16	0.1955	0.1935	0.1955	0.1948	0.0298	121	120	119	120.00
17	0.1985	0.1935	0.1940	0.1953	0.0300	127	127	121	125.00
18	0.1995	0.1965	0.1930	0.1963	0.0303	122	120	120	120.67
19	0.2180	0.2165	0.2180	0.2175	0.0371	130	126	125	127.00
20	0.2170	0.2180	0.2185	0.2178	0.0372	130	126	125	127.00

The data reveals that the field strength did increase consistently with the cross-sectional area. From the graph in Figure 9, it is seen that one of the readings is off the trend from the others.

The problem of the DC electromagnet being insufficient to magnetize the steel sample completely was observed again. This is because at higher values of the cross-sectional area the graph becomes flat, which means that the magnetization is insufficient. Better readings are anticipated with the use of a stronger electromagnet when the specimens can reach a level near to saturation.

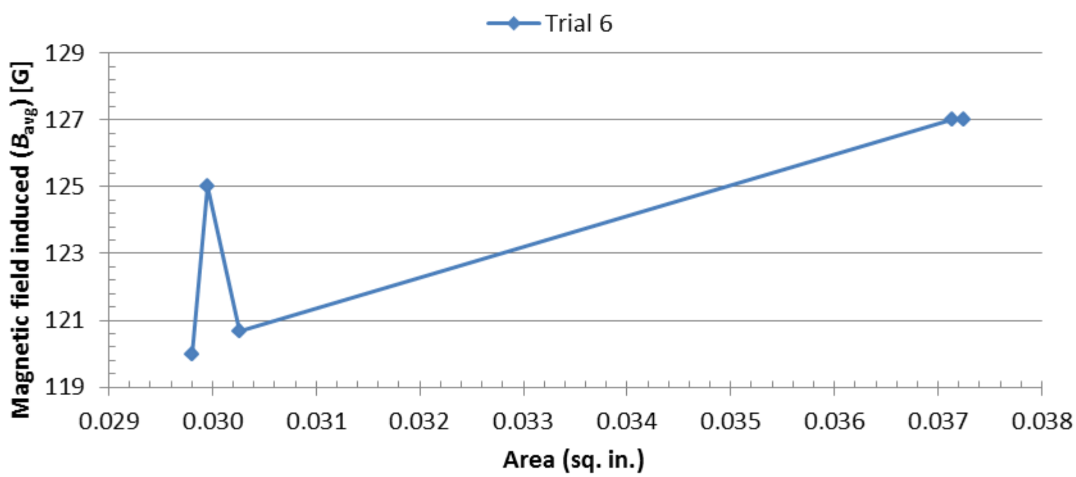

Figure 9. Area vs. induced magnetic field strength for Trial 6.

6.4 Experiment 4: Trial using rebar

In addition to the trials described in the previous sections, trials were also conducted with rebar specimens. The steel specimen used was 0.5 in diameter and 6 in long. The results are shown in table 7 and the graph of the magnetic field against the cross section area is shown in Figure 10. The magnetization procedure was the same as described earlier. Rebar was used in order to determine the usefulness of the DC electromagnet in conducting advanced experiments.

Table 7. Magnetic flux density B [G], induced in steel rebar specimen with diameter d [in.] for Trial 7.

Diameter (d) [in.]	Area [in^2]	Magnetic Field (B) [G]
0.4863	0.1856	75.7
0.4873	0.1864	65.5
0.4883	0.1872	59.0
0.4908	0.1891	62.0
0.4915	0.1896	61.2
0.4930	0.1908	80.5
0.5080	0.2026	54.0
0.5322	0.2223	53.0

The data collected in this case showed that the specimen with higher cross-sectional area was induced with lesser magnetic field strength in contrast to the previous trials 1-6. This could again be mainly due to the inability of the DC electromagnet to magnetize the thicker rebar compared to the thinner rods used in the previous trials. A peak and dip can be seen in Figure 10 marked in red. This is most likely due to the ribs in the rebar. When the sensor was placed on a rib, the reading observed was much higher than if it were placed on a smooth spot on the bar.

The electromagnet is again unable to magnetize the larger cross-sectional area of a rebar specimen. The curve in Figure 10 is decreasing rapidly instead of rising with the cross-sectional area.

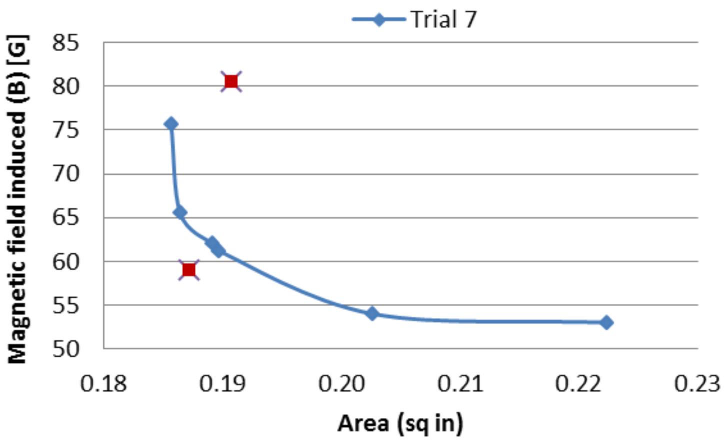

Figure 10. Area vs. induced magnetic field strength for Trial 7 using rebar.

6.5 Analysis and conclusions from laboratory experiments

In the initial experiments, the steel specimen was magnetized by direct contact between the sample and the rod. In the later experiments, an air-gap was introduced between the sample and the electromagnet to simulate a concrete cover, since air has roughly the same magnetic reluctance as concrete. It was felt that experiments with concrete gaps or reinforced concrete could be done later when the proof-of-concept was achieved.

Twenty specimens of steel bar of various alloys and sizes were tested. The test specimens included samples of rebar. The remnant field and the magnetic field were measured. The position of the bar relative to the electromagnet was also varied. Overall, it was observed that the specimens with smaller diameters are magnetized to a greater percentage of saturation than those with greater diameters. The specimens with diameters more than 0.22 in. are magnetized only at the surface in contact with the pole of the electromagnet. It is clear from the low level of remnant magnetic fields and magnetic fields reached in the larger steel bars that the field projection of the present electromagnet is very low for the specimens being tested. This divergence is most likely due to the fact that the cross-sectional area of these specimens is too large for the present electromagnet to completely magnetize the specimen and generate a good magnetic field. Thus, in order to achieve saturation and complete volume magnetization of a 0.5 in. rod specimen, an electromagnet with a higher field intensity is needed.

After taking all these inferences into consideration, it was decided to use a stronger electromagnet which can produce a higher projection of magnetic field. For this the lifting magnets manufactured by Ohio Magnetics, Inc, Maple Heights, Ohio, were considered as an alternative after the research team’s visit to their facility.

7. Experiment using Stronger Electromagnet at Ohio Magnetics, Inc.

The aim of conducting the experiment at Ohio Magnetics was mainly to observe the magnitude of the magnetic field induced in the steel specimen using a stronger electromagnet. Based on the results obtained, a decision would be made whether a similar or modified electromagnet could be used to do further experiments in the research lab.

Ohio Magnetics specializes in the design and production of commercial magnets used in salvage yards and recycling facilities. A 25 in. diameter model POW-R-LITE electromagnet was used at their facility to investigate if a larger electromagnet would help get more accurate and consistent readings when an air gap was introduced. Figure 11 shows the experimental setup.

Figure 11. Experiment setup at Ohio Magnetics using POW-R-LITE.

The air gap tested with this electromagnet was 2.875 in. which is beyond what will be seen in the field. The test set-up was not known until arrival at the facility and proper action could not be taken to ensure a proper more adequate air gap. At this air gap, the specimens were able to be magnetized, and the results were consistent with our earlier trials. From the data in Table 8, it is seen that as the area of the specimen increased, the flux density reading also increased gradually. This is also clear from the graph in Figure 12.

Table 8. Magnetic flux density B [G], induced in steel specimen with diameter d [in] using POW-R-LITE.

Specimen #	d (in)	Area (in^2)	B (G)
1	0.1250	0.0123	400
2	0.1875	0.0276	415
3	0.2500	0.0491	505
4	0.3750	0.1103	730
5	0.5000	0.1963	847

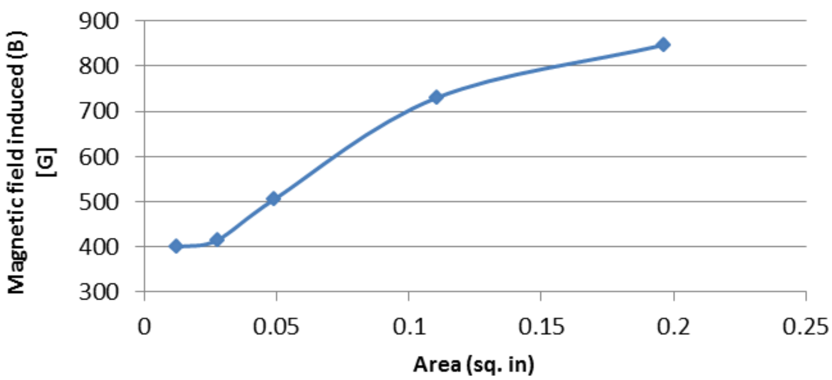

Figure 12. Area vs. induced magnetic field strength for specimens using POW-R-LITE at Ohio Magnetics.

This supports the initial hypothesis that the induced magnetic field is proportional to the cross-section of the bar or rod under magnetization. Thus, the results indicate that in order to obtain effective magnetization a stronger electromagnet is required.

8. Laboratory Experiments using Flat Stock

In order to investigate further the issue of achieving saturation of the specimen under magnetization it was decided to modify the geometry of the specimen. As per the magnetization principle, in order that the specimen is magnetized to a level near its saturation point it is necessary that maximum magnetic flux lines flow thought it. When using a bar which has a circular cross-sectional area, the area under magnetization is not uniformly in contact with the pole of the electromagnet. To have maximum area under the influence of magnetic flux lines, flat bars were thought to be better suited. It was felt that if the relationship between the induced magnetic field and cross-sectional area was proved using flat bars, it would be a good tool to decide the scope for this project. This was also recommended to the research team by the engineers at Ohio Magnetics. Hence, this experiment was conducted using the present DC electromagnet in the laboratory facility at UT.

The flat bar specimen was 2 in. wide and 8 in. long. The thicknesses of the specimens were 0.125, 0.1875, and 0.375 in. The parallel pole DC electromagnet used in the laboratory previously was used for this experiment. The results of these experiments can be seen in Table 9 and Figures 13 and 14. It can be seen from Figure 13 that the induced magnetic field in the specimen reduces with the increase in the air gap between the specimen and electromagnet. This means that in order to magnetize the specimen at higher air-gaps (around 1 to 2 in) a stronger electromagnet is needed. A distinction between cross-sectional areas cannot be made beyond a 0.25 in. air gap.

Table 9. Readings of magnetic flux density B_{avg} [G] for flat stock specimens.

Air gap (g) [in]	Measured flux density (B_{Avg}) [G]		
	Specimen #1 (0.25 in^2)	Specimen #2 (0.375 in^2)	Specimen #3 (0.75 in^2)
0.25	511.5	478.50	494.50
0.56	115.5	126.00	125.75
1.00	30.5	34.50	34.15
1.50	7.0	9.25	9.00
2.00	3.0	3.00	3.00

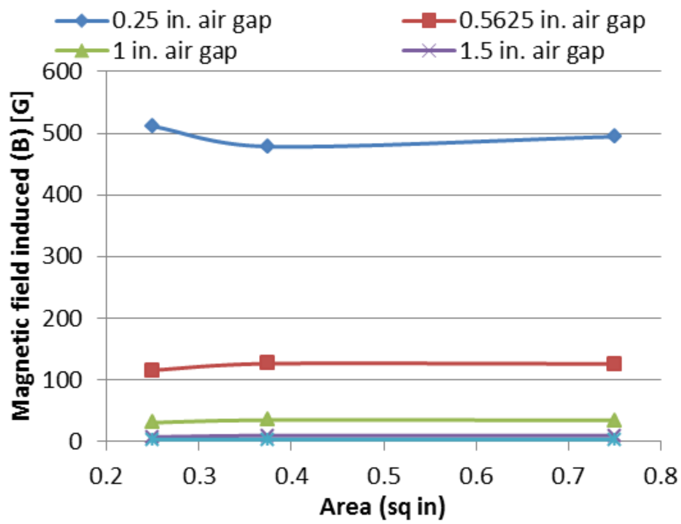

Figure 13. Induced flux density vs. cross-sectional area plot for magnetization of flat specimen.

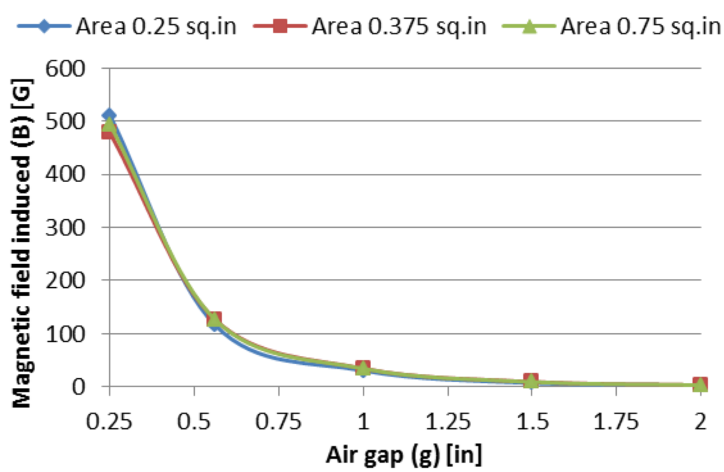

Figure 14. Flux density vs. air gap plot for magnetization of flat specimen.

Compared to previous results, the graph in Figure 14 shows very little distinction between cross-section areas, roughly in the range of 0.1 sq in. From Figure 15 it is clear that the magnetic field induced in the specimen does not reflect the cross-sectional area for large air-gaps.

9. Conclusions from Phase I of the Project

The research team's work shows that a magnetic sensor applied from one side can detect the cross sectional area of a bar, but it also revealed the shortcomings of the present test setup and understanding of the phenomena. All experiments point to a common problem of insufficient magnetization with the present parallel pole DC electromagnet. This has led the team to believe that the electromagnet design needs to be thoroughly improved to bring about magnetization in the specimen closer to their saturation point. From the results, it is clear that magnetization of the specimens closer to saturation is necessary to distinguish the loss of area due to corrosion. This requires the research team to develop the design for an electromagnet well suited to our purpose.

Using a yoke-shaped electromagnet will have better magnetization of the steel sample along its length. Increasing the magnitude of the magnetic field intensity is necessary to achieve a higher induced magnetic field in the steel sample. A higher resolution will be available to differentiate between the readings obtained from the loss of area and the normal surface. The reluctance of the air gap (or concrete material) can be overcome using a higher magnetization.

Results of the objectives for this study include the following:

- "Develop a prototype sensor based on magnetic principles and determine if it is promising enough to merit further development." The experimental work and the literature review support that electromagnet detection will work. At this time, no fatal flaw has been discovered
- "Develop and execute a testing protocol to verify the sensor's ability to detect the cross sectional area of corroded prestressing strand in the laboratory. There will be a progression of experiments examining the effect of gaps between the electromagnet and the specimen. This will culminate in the measurement of specimens embedded in concrete." This project exposed the difficulties with the existing small parallel pole electromagnet. Design and procurement of a new electromagnet has begun. Future experiments will be carried out with the new electromagnet.
- Seek external funding to further the sensor development. Opportunities for funding are being explored, but no proposals have been submitted yet.

The proposed phase II work moves toward the development of a practical sensor. Such a sensor, once developed, should be able to estimate the area of exposed or hidden corroded strands. The development of a magnetic sensor will make inspection of prestressed concrete bridges easier and more cost effective by assisting in effective maintenance planning. With a larger electromagnet and a better understanding, both experimental and theoretical, of the effect of air gaps and the gaps filled with concrete, the team expects to develop a sensor capable of finding a consistent relationship between magnetic field strength and the cross sectional area of the specimens in a laboratory setting. A new objective for phase II would be - "Develop a relationship with a commercial electromagnet manufacturer." The work with Ohio Magnetics, Inc. has shown that a large commercial international caliber electromagnet manufacturer has knowledge and resources that are invaluable in the development of an electromagnetic sensor.

In the development of this sensor, the primary risks are the difficulty of magnetizing the specimen from one side and uncertainty about the effects of concrete. Other risks are metallurgy, stress state of the strand, complications with weaving of the strand, and that the corrosion products or water in the corrosion products will interfere with reading the magnetic properties of the strand. This risk is mitigated by the authors' experience that even small changes in area can be detected. Outreach, such as submitting a TRB proposal and networking, helps the team to get feedback about risk. As the research was pursued, the team has learned more about the nature of the magnetic signal and the influence of the corrosion products.

10. References

Abi Shdid (2006), C. and M.H. Ansley "Visual Rating and Strength Testing of 40-Year-Old Precast Prestressed Concrete Bridge Piling", Transportation Research Record: Journal of the Transportation Research Board No. 1975, July 2006.

Federal Highway Administration (FHWA 2010) "Inspection Methods and Techniques to Determine Non-visible Corrosion of Prestressing Strands in Concrete Bridge Components" TPF-5(167), http://www.pooledfund.org/projectdetails.asp?id=393&status=6, accessed April 30, 2010.

Fernandes (2010), B, "Nondestructive evaluation of deteriorated prestressing strands using magnetic field induction," Thesis, The University of Toledo.

Ferroni (2007) K., "Inspection Methods and Techniques to Determine Non-visible Corrosion of Prestressing Strands in Concrete Bridge Components" http://rip.trb.org/browse/dproject.asp?n=15188, accessed Nov. 16, 2008.

Hillemeir (1998), B. and H. Scheel, "Magnetic detection of prestressing steel fractures in prestressed concrete", Materials and Corrosion, Vol. 49, pp 799-804.

Lakeshore Gaussmeter for Magnetic Measurements – Handheld Gaussmeter – Model 410 – Product Overview, http://www.lakeshore.com/mag/ga/gm410po.html

Mihalache (2001), O., G. Preda, N. Yusa and K. Miya, "Experimental Measurements and Numerical Simulation of ID and OD Signals in Plate Ferromagnetic Materials Using Magnetic Flux Leakage", Proc. Of the 4th Japan-Central Europe Joint Workshop on Energy and Information in Non-linear Systems, Nov. 10-12, 2000, Brno, Czech Republic.

ODOT (2008) Ohio Department of Transportation Request for Proposals "Structural Evaluation of LIC-310-0396 Box Beams with Advanced Strand Deterioration, PS-08-11.

Rumiche (2008), F., Indacochea and M.L. Wang, "Detection and Monitoring of Corrosion in Structural Carbon Steels Using Electromagnetic Sensors", Journal of Engineering Materials and Technology, ASME, Vol. 130.

Scheel (1997), H.: Spannstahlbruchortung an Spannbetonbauteilen mit nachtraglichem Verbund unter Ausnutzung des Remanenzmagnetismus, Dissertation, Technical University, Berlin.

Scheel, H. and Hillemeier (1997), B., "Capacity of the remnant magnetism method to detect fractures of steel in tendons embedded in prestressed concrete", NDT & E International, Vol. 30, No. 4, pp 211-216.

Scott (2006), C.M., PA Non-composite Adjacent Box Beam Bridges A presentation adapted from the AASHTO T-18 Bridge Inspection Technical Committee Meeting, June 2006.

Wade (2010), J. D., "Magnetic sensor for nondestructive evaluation of deteriorated prestressing strand," Thesis, The University of Toledo.