Detection of Breaks in Reinforcing Bars with the Magnetic Flux Leakage Method

Thomas Wolf[1], Thomas Vogel[1]

[1] Institute of Structural Engineering – ETH Zurich, Wolfgang-Pauli-Strasse 15, 8093 Zurich, Switzerland

ABSTRACT: The magnetic flux leakage method offers the potential to detect breaks in reinforcing bars resulting from fatigue or pitting corrosion in a non-destructive way.

This paper presents on-going and future research, covering the detection of breaks in different specimens with reinforcement layouts by measuring the magnetic flux density. Criteria to find an applicable magnet as well as sensors for the measurement system are given. The development of a guidance system and the data acquisition are described as well.

1 INTRODUCTION

The comparison of calculated reinforcement stresses and experimental fatigue limits provided by the codes shows that concrete structures loaded by heavy traffic are subject to fatigue in the long term. Nevertheless, almost no breaks of reinforcing bars have been reported so far. Reasons may be that breaks are not actively searched and that fatigue breaks are hard to detect by non-destructive testing methods.

The following methods are considered to detect broken reinforcement bars:

Although a visual inspection of the reinforcement is not possible without damaging the structure, cracks at the concrete surface can serve as indicators for fatigue failures of the reinforcement.

Radiography with X-rays offers the possibility to locate the position of the reinforcement. Hillemeier and Scheel (2002) reported that X-ray methods require a detectable break width and a separation between the reinforcing bars. Due to the potential damage to human beings, field applications of X-rays are further restricted.

Acoustic emissions are elastic waves generated by the sudden release of energy during the failure of a material propagate inside the structure. Sensors mounted on the structure surface detect the elastic waves. Different arrival times at the sensors allow the localization of the source of the acoustic emissions. Acoustic monitoring is able to detect wire breaks in post-tensioning tendons as well as concrete cracking (Vogel *et al.* (2006)) and is connected to ongoing deterioration processes. The actual state of the reinforcement cannot be assessed.

The magnetic flux leakage (MFL) method makes use of the fact that a separation of a permanent magnet into two parts changes the surrounding magnetic field considerably. It has been applied in material inspections for more than eighty years and since the nineteen-eighties the method is used to detect breaks in prestressing steel of pretensioned and post-tensioned concrete structures (Scheel (2006)).

2 RESEARCH PROGRAM

The aim of this project is to explore the potential and the limits of the MFL method. An attempt is made to detect breaks in several reinforcement layouts and to gain experience in interpreting of experimental data.

Software to interpret the measured data graphically will be developed. The measurement system will consist of magnets, sensors as well as a modular positioning and control system.

Emphasis is placed on typical patterns of the measured magnetic flux density for each setting of predefined reinforcement layouts. This kind of information will enable automatic detection breaks.

2.1 Physical Principle of the MFL Method

By magnetizing a reinforcing bar becomes a bar magnet (Fig. 1) with a respective magnetic field. The concentration of streamlines of the field is expressed by the magnetic flux density, which can be measured by a Hall sensor moved along the reinforcing bar (Fig. 2).

At the location of a break new magnetic north and south poles arise and the respective magnetic flux field shows a leakage expressed by a change of sign (Fig. 3). The characteristic pattern, which is called peak-peak-amplitude, allows the detection of breaks.

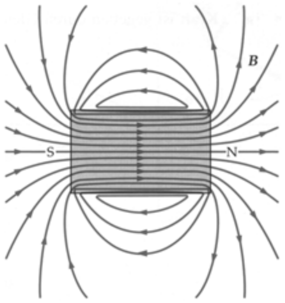


Figure 1.Magnetic field of a bar magnet (Tipler and Mosca (2004)).

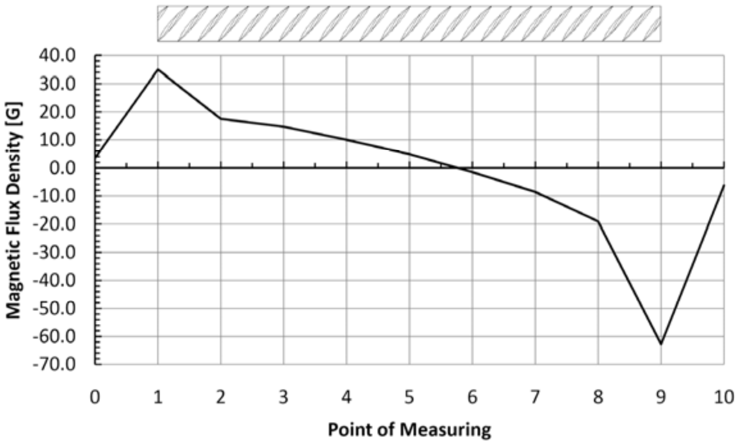


Figure 2. Typical measuring curve of an unbonded reinforcing bar with start and end pole.

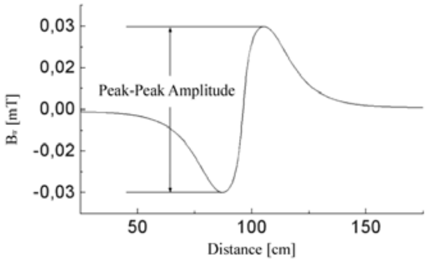


Figure 3. Peak-peak-amplitude of transverse component of magnetic leakage field at the point of measuring (according to Scheel and Hillemeier (1997))

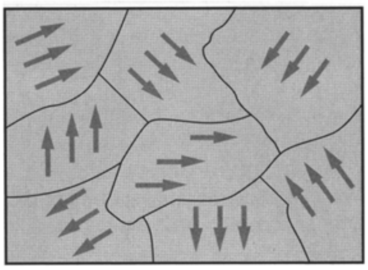
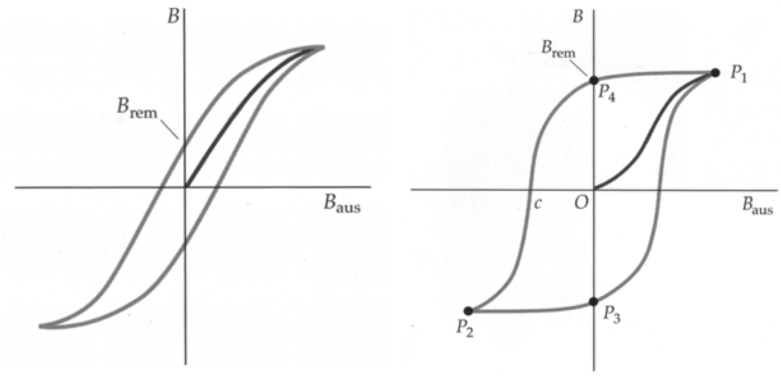


Figure 4.Weiss domains (Tipler and Mosca (2004)).

To achieve a homogenous magnetizing, the magnetic history of the reinforcing bar has to be erased. This means that all previous magnetic influences and processes since the fabrication of the bars, e.g. from lifting magnets or mechanical actions, have to be cleaned and a defined magnetization has to be achieved. Areas with a uniform direction of the magnetic field at the atomic level are called Weiss domains. They develop during the cooling process and show random directions (Fig. 4). The unaligned Weiss domains are the reason for disturbances in the magnetic field. The domains can be newly arranged by an external magnetic field, e.g. from a permanent magnet or an electromagnet, resulting in a strong residual magnetic field around the ferromagnetic body.

Prestressing steel and mild reinforcement vary in their magnetic properties. Prestressing steel is a magnetic hard material. The direction of Weiss domains can only be changed by using a strong external magnetic field like that one of an electromagnet. Weiss domains of mild reinforcement can be changed by a weaker magnetic field from a permanent magnet.



a) b)

Figure 5. Magnetic hysteresis of a magnetically mild material (Tipler and Mosca (2004)).

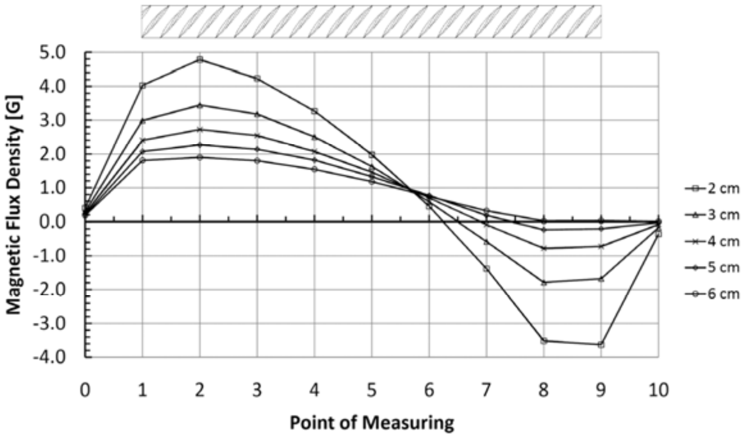


Figure 6. Magnetic flux densities for different distances between bar and sensor.

Fig. 5a displays the hysteresis for a magnetically mild and Fig. 5b for a magnetically hard material, respectively. The material is magnetically saturated when all Weiss domains are aligned; corresponding to the points P1 and P2 in Fig. 5b. When the external magnetic field is switched-off, the magnetic flux density drops along the saturation curve and the residual magnetization remains (points P3 and P4 in Fig. 5b).

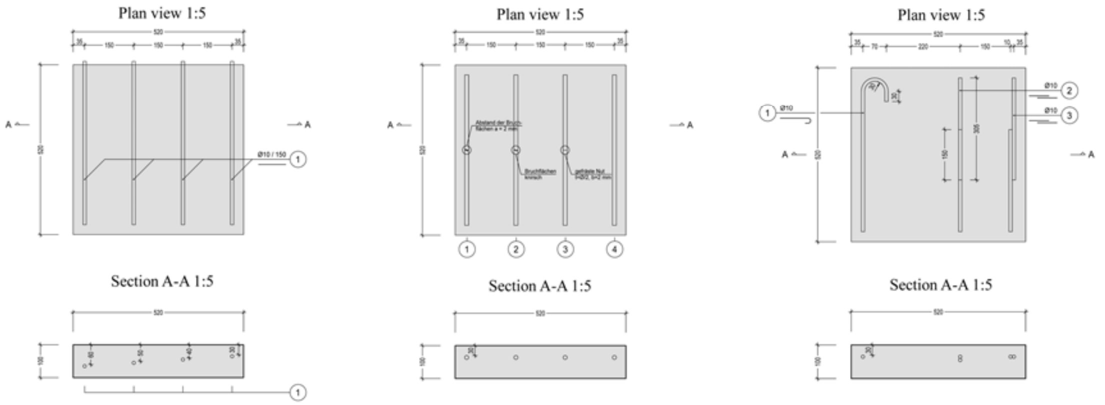
After the magnetization the flux density can be measured with Hall sensors. Since the flux density decreases by the power of three with the distance, the spacing between bar and sensor is crucial. Fig. 6 shows the amplitudes of magnetic flux densities for different distances between reinforcing bar and sensor.

2.2 Preliminary tests

Tests with permanent magnets and an analogical measurement instrument were performed with unbonded reinforcing bars. After magnetizing the flux densities were measured, recorded and compared with the values from theoretical considerations. The compared data correlate well on the first sight. As can be seen in Fig. 6, the point of zero crossing is not in the center to the bar and the signal amplitudes at the bar ends are not equal. The reasons for these deviations will be evaluated in further research.

In addition to the unbonded reinforcing bars three concrete specimens with predefined reinforcement layouts were casted. In the first specimen (Fig. 7a) the concrete cover is varying and in the second one (Fig. 7b) the bars 1 and 2 origin from fatigue tests were casted in with different distances of the fracture surfaces. The third bar has been notched with the depth of the half bar-diameter whilst the fourth has been damaged by pitting corrosion. The third specimen (Fig. 7c) has a hooked reinforcement on the left side and splices with different orientation on the right side.

The reinforcement was magnetized from the concrete surface with a permanent magnet. The magnetic flux densities have been measured at predefined measuring points shown in Fig. 8 and they are visualized in a three dimensional drawing (Fig. 9). The measured flux densities of the magnetic field at the top of the specimen correlate very well with those of the side, even if the measured components are not the same but in either case perpendicular to the respective surface.



a) b) c)

Figure 7. Specimens with different reinforcement layouts.

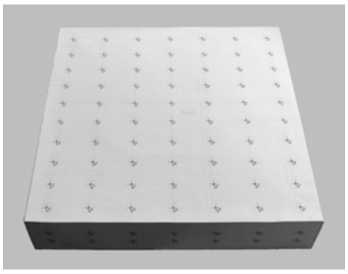


Figure 8. Arrangement of reading points.

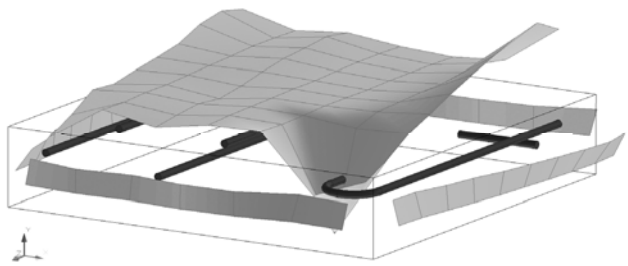


Figure 9. Visualization of a magnetic field.

Preliminary tests have shown that under laboratory conditions permanent magnets can be used for magnetization of reinforcing bars. Measurements with an analogical instrument are not practical because the logging is inexact, time-consuming and the sampling-rate is too low.

2.3 *Planned Research*

Due to the fact that the hysteresis of reinforcing steel differs from that one of prestressing steel, further investigation on this topic is needed. Findings of researchers working with prestressing steel are the basis for developing a magnetic measurement system for mild reinforcement.

Two known methods, which are able to detect breaks in prestressing steel, use electromagnets (Mietz and Fischer (2005)) because a strong magnetic field is needed to saturate the magnetically hard material. In the up-coming tests, the suitable type of magnets is identified to reach a complete magnetic saturation of the reinforcing bars. At the moment magnets with a $Nd_2Fe_{14}B$ alloy, which are also called Neodymium magnets, are known to be able to magnetize unbonded reinforcing bars. Permanent magnets must be heavier and larger when the distance between the bar and the magnet increases. In this case, an electromagnet could be an option. Electromagnets can generate a stronger magnetic field without increasing their dead weight. Disadvantages compared to permanent magnets are the higher initial costs and the additional power supply. The mass of the magnet is crucial as soon as measurements will be performed at vertical or even overhead surfaces.

The measurement system will also include sensors that are able to measure the magnetic flux density of bars with a concrete cover up to about 6 cm.

The earth magnetic field has an influence on the flux densities of the reinforcement. Laboratory experiments have shown that different magnetic flux densities can be measured after the orientation of the reinforcing bar or of the whole specimen has been changed. So far, the flux densities have been measured with an analogical set-up (Fig. 10) and a low resolution of measuring points. A high resolution of measuring points is essential, however, to detect breaks.

Because a measuring grid with a spacing of 1 to 5 mm is necessary, only an automized data acquisition allows for recording in an acceptable time. Next tests will be made with the MicroMag 3-Axis Magnetometer (Pni-Sensor-Corporation (2009), Fig. 11). A measurement range of $\pm 1100\ \mu\mathrm{T}$ and a resolution of $0.015\ \mu\mathrm{T}$ allows for measuring small differences in the flux density. The necessity to measure all spatial components of the magnetic field will be checked, too.

An automation of the positioning system that can move the sensors on the concrete surface has to be developed. The coordinates of every measuring point will be sent to the computer and saved to a file. A rail system and a robot arm are possible options.

The measured data will be displayed online three dimensionally on a monitor. Patterns that may indicate possible breaks can be identified and the engineer in situ can run more detailed investigations at these locations.

Since a tangible lack of information about the progression of fatigue failures in concrete structures exists, large scale tests on reinforced concrete frames subjected to cyclic loading will be performed at our institute to investigate the load bearing behavior under service conditions. Experiments on these large scale tests with the MFL method as well as the application of acoustic monitoring are planned to detect and localize breaks in the reinforcement. Further tests on predefined reinforcement layouts, including splices, bending ups, hooks and crossed reinforcement, will be carried out. Parameters like concrete cover, spacing of bars, width of fracture surfaces of reinforcing bars, disturbing signals caused by ferromagnetic built-in components and steel properties will be varied.

As a result of the analysis, typical patterns of the flux density for each setting are expected.

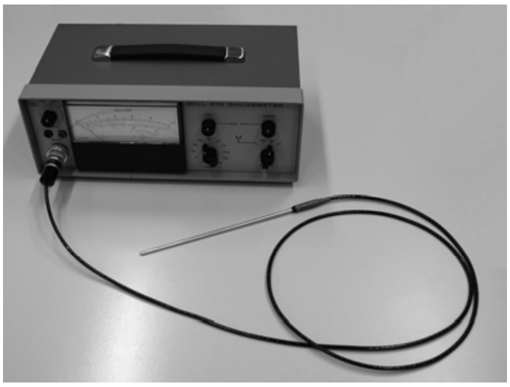


Figure 10. Gaussmeter – Analogical measuring instrument.

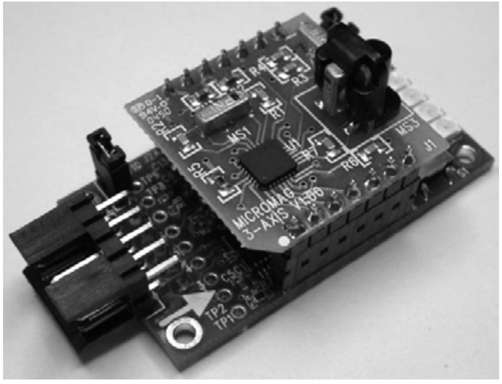


Figure 11. 3-Axis magnetometer (Sparkfun-Electronics (2009)).

A library of these patterns offers the option to detect breaks automatically. The measured flux densities could be compared with the known patterns. They will be marked when a change of sign exists and the signals does not match with the known patterns.

3 CONCLUSIONS AND OUTLOOK

Usually, bridge assessment is based on visual and invasive inspections. However, the information provided is often incomplete and costly. The magnetic flux leakage method has the potential to detect breaks in reinforcing bars non-destructively. Preliminary tests to investigate the possibility of magnetizing reinforcing bars showed that the magnetic fields of Neodymium magnets are strong enough for single bars.

The tests showed that due to a low resolution of measuring points analogical measurement instruments can only be used for smaller laboratory tests. The magnetic flux densities of bonded and unbonded reinforcing bars can be measured. So far, the spatial resolution of the measurement is not high enough to identify possible breaks. For known breaks of unbonded reinforcing bars, the typical change of sign in the flux density could be found by reducing the spacing of the measuring points.

In future steps, the Neodymium magnets will be tested on bonded reinforcing bars and a magnetometer for the application on different test arrangements will be checked. Since the data acquisition will be carried out electronically, the spatial resolution can be increased.

An automatic measurement requires a guidance system that moves the sensors on the concrete surface. Therefore, non-ferromagnetic material has to be used for all components.

With the installation of data acquisition software that can display the values three dimensional, real-time operations will be possible.

Measurements on large scale tests of reinforced concrete frames and on different reinforcement layouts will show typical patterns in the flux density. The patterns will be collected in a library to allow for identifying breaks automatically.

4 AKNOWLEDGEMENT

The authors gratefully acknowledge the contribution of P. Fehlmann, S. Fricker, D. Werne, E. Honegger and C. Senn, Institute of Structural Engineering (IBK) ETH Zurich.

5 REFERENCES

Hillemeier, B. and Scheel, H. (2002). *Non-Destructive Location of Prestressing Steel Fractures in Post-Tensioned and Prestressed Concrete*; Transportation Research Board (TRB) Committee A2C03, Washington D.C., USA; January 16., 2002; pp. 1-11.

Mietz, J. and Fischer, J. (2005). *Verifizierung zerstörungsfreier Prüfverfahren zur Detektion von Spannstahlschäden an Spannbetonbauteilen mit nachträglichem Verbund*; Beton- und Stahlbetonbau; 100, 8; pp. 656-663.

PNI-Sensor-Corporation (2009). SmartSens MICROMAG 3; http://www.pnicorp.com/products/all/micromag-3

Scheel, H. (2006). *Spanndrahtbruchortung mit der magnetischen Streufeldmethode*; Beton- und Stahlbetonbau; 101, 8; pp. 614-621.

Scheel, H. and Hillemeier, B. (1997). *Capacity of the Remanent Magnetism Method to Detect Fractures of Steel in Tendons Embedded in Prestressed Concrete*; NDT&E International; 30, 4; pp. 211-216.

SparkFun-Electronics (2009). MicroMag 3-Axis Magnetometer; http://www.sparkfun.com/commerce/product_info.php?products_id=244

Tipler, P. A. and Mosca, G. (2004). *Physik - Für Wissenschaftler und Ingenieure*; Elsevier GmbH, München; 1388 pp.

Vogel, T., Schechinger, B. *et al.* (2006). *Acoustic Emission Analysis as a Monitoring Method for Prestressed Concrete Structures*; EC NDT 9th European Conference on NDT, Berlin; September 25-29, 2006.