Experimental trials on the detection of reinforcement breaks with the magnetic flux leakage method
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ABSTRACT: The magnetic flux leakage method is used to detect failures in ferromagnetic materials since over 80th years and now this method is going to be applied in detecting reinforcement breaks of concrete specimens. After a short introduction including the state-of-the-art and the physical principles of the magnetism and, in particular, the leakage method, the paper presents the on-going research. Investigations on the detection of breaks in predefined reinforcement layouts as well as measurements on a large-scale experiment are described. Explanations about the first trials on displaying the measured data are also given. The paper concludes with an outlook of the future work that achieves the development of a guidance system which is necessary for an automatic measurement system.

1 INTRODUCTION

Hardly any fatigue breaks of reinforcing bars in concrete structures have been reported so far. Reasons may be that fatigue breaks are not actively searched for and that they are hard to detect by non-destructive testing methods.

Non-destructive testing methods such as visual inspection of reinforcing bars are not efficient enough to investigate larger parts of bridges under real conditions. The reinforcement is not visually accessible to the inspector because of the concrete cover. Another possibility to investigate the reinforcement is the application of radiography with X-rays but it is restricted due to its potential damage to human beings. The acoustic emission analysis has the disadvantage that only changes of the condition over time can be measured and not the condition itself at the moment of the inspection (Vogel et al. (2006)). For the measuring of changes of the investigated structures, the technical equipment has to be installed.

Since the nineteen-eighties the magnetic flux leakage (MFL) method is used to detect breaks in prestressing steel of pretensioned and post-tensioned concrete structures (Scheel (2006)).

2 MAGNETIC FLUX LEAKAGE METHOD

The MFL method makes use of the fact that a separation of a permanent magnet into two parts leads to a new pair of magnetic poles and changes the surrounding magnetic field considerably.

An automatic measurement system will be developed and thus four major issues have to be studied: the physical principles of magnetism, the investigated material, the technical measurement equipment and the data acquisition and analysis.

The measurement system itself will consist of magnets, sensors and an automatically working modular positioning and control system. Preliminary tests with different technical and electronic equipment such as magnets and measurement devices have been performed to gain experience. Initial steps in data acquisition and analysis have also been carried out.

2.1 Physical principle

The magnetic flux density is expressed by the concentration of magnetic streamlines. Magnetic streamlines are a property of a magnetic field which is a vector field that shows the direction and strength at the examined position.

The magnetic fields of a bar magnet and of a magnetized reinforcing bar are similar. In both cases the magnetic streamlines match very well because the fields have the same shapes.
The break of a bar magnet leads to a new pair of magnetic poles at the edges of the break which alter the magnetic streamlines (Fig. 1). The new pair of poles leads to a change of the field direction (Fig. 2) in the magnetic flux density, which can be measured by sensors.

At the atomic level the bar magnet is composed of elementary magnets which are dipoles with small magnetic fields. All dipoles have the same direction resulting in a strong magnetic field which surrounds the area of the bar magnet.

The material of a steel bar is also composed of elementary magnets. When the steel is manufactured, different areas with the same direction of the elementary magnets develop during the cooling process.

These areas, which all have a uniform direction of the magnetic field at the atomic level, are called “Weiss domains” (Fig. 3). In contrast to the bar magnet, the Weiss domains of a steel bar are undirected among each other and a global magnetic field does not exist.

The Weiss domains can be directed by an external magnetic field, e.g. from a permanent magnet (Fig. 4) or an electromagnet, resulting in a strong residual magnetic field surrounding the steel bar.

If the external magnetic field is strong enough, the material achieves magnetic saturation, i.e. all Weiss domains are aligned in the same direction. A stronger external magnetic field does not lead to a stronger residual magnetization. In the hysteresis of Figure 5 the magnetic saturation is labeled by the points P1 and P2. 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, respectively).

2.2 Technique of magnetization

Once the reinforcing bar is fabricated, it gets a magnetic history. The history change every time there is contact with another magnetic field such as lifting magnets or magnetizations of former magnetic-based investigations.

When the reinforcing breaks or when it is mechanically processed, the Weiss domains will be un-
directed locally and the magnetization disturbs. Therefore previous magnetic influences have to be erased otherwise magnetically sensitive measurements might show anomalies. A defined magnetization achieves by repeated movements of a permanent magnet alongside the reinforcing bar (Fig. 6). The Weiss domains adapt their magnetic orientation to the one of the external magnetic field during every passage of the magnet.

After the magnetization of the reinforcing bar and prior to the measurement, the external magnet has to be removed. The measurement is carried out with a MicroMag 3-Axis Magnetometer (Pni-Sensor-Corporation (2009)). The magnetometer has to be moved with a specific distance alongside the reinforcing bar to measure the magnetic flux density of the residual field of the bar. Since the flux density decreases by the power of three with the distance, the spacing between steel bar and sensor is crucial.

The measurement curves for different distances between sensor and steel bar are shown in Figure 7. The distances vary from 16 to 46 mm. The curve with the large amplitudes belongs to the distance of 16 mm and the one with the smallest amplitudes to the distance of 46 mm. At the top of Figure 7, the gap in the reinforcing bar of about 2 mm is shown.

When the measurement is completed the data analyzed manually and the measured values are displayed graphically.

2.3 Technical equipment

Four subjects have to be investigated to develop an automatic measurement system: the magnets, the sensors, the positioning system and the data acquisition. First experiments have been performed with simple equipment consisting of a small permanent magnet and an analogical measurement set-up.

The magnetic field of the magnet was strong enough to magnetize a separated reinforcing bar when the distance between bar and magnet was small.

When the distance of both was increased and the reinforcing bar casted-in, the magnetic field was too small for a feasible measurement. The volume of a permanent magnet is crucial for the strength of its magnetic field. The first magnet with a diameter of 20 mm and a height of 10 mm has a 6 times smaller volume than the one currently used with a diameter of 35 mm and a height of 20 mm.

At the moment, magnets with an Nd₂Fe₁₄B alloy, so-called Neodymium magnets, are used for the magnetization of the reinforcing bars.

The quality of the used materials differs slightly between the smaller and the bigger magnet. The combination of both, the size of the magnet and the quality of the material, leads to a considerable difference of the adhesive force. The smaller magnet has an adhesive force of about 110 N and the bigger one of about 420 N (Webcraft-Gmbh (2009)).

The elementary magnets of the reinforcing bar have to be aligned by the magnetization longitudinal to the bar axis. The distance between the magnetic poles increases when four magnets are assembled to one big magnet as can be seen in Figure 4.
In that case the parallel part of the external magnetic field flowing through the reinforcing bar (accented with a circle) becomes larger (Fig. 8). It therefore aligns the elementary magnets in the longitudinal direction of the bar as requested. With the current constellation of the size and material of the magnet, a complete magnetic saturation cannot be achieved.

First measurements were carried out with an analogical set-up, a so-called Gaussmeter. The measurements with the Gaussmeter were to slow because the sensor had to be positioned by hand for every point of measurement. This slows down the process of measuring dramatically.

The resolution of the measurements was low since the number of measuring points was limited with respect to the needed time. Additionally, the measured values had to be written by hand.

Now the electronic device MicroMag 3-Axis Magnetometer is used to measure the magnetic flux density because an automated data acquisition is needed. This allows recording the data in an acceptable time. The MicroMag has a measurement range of \( \pm 1100 \, \mu T \) and a resolution of 0.015 \( \mu T \) which allows measuring small differences in the magnetic flux density. It is also able to measure the three spatial components of the magnetic field.

So far, no automatic positioning system is part of the measurement setup but it is planned to integrate one. The position along the reinforcing bar will be measured by a rotation encoder.

Since the MicroMag is being used for the measurements the data is collected by an amplifier and stored on a computer in an ASCII format which can be read or imported by nearly all programs.

Since the number of values increased that much the data analysis is done with Matlab.

3 RESEARCH PROGRAM

The aim of this research project is to identify the potential and the limits of the MFL method. An automated measurement system consisting of magnets, sensors as well as a modular positioning system will be developed including a graphic interpretation of measured data. Emphasis is placed on the collection of typical patterns of the measured magnetic flux densities for each setting of predefined reinforcement layouts. The comparison of these patterns with measurements in the field will enable an automatic detection of breaks.

3.1 Laboratory experiments

First of all, tests with permanent magnets and an analogical measurement equipment were performed with unbonded reinforcing bars. After the magnetization with the small Neodymium magnet, the magnetic flux density was measured and recorded.

Investigations on different distances between the reinforcing bar and the sensor were carried out and the results were displayed graphically (Fig. 7).

As can be seen in the graph, the amplitudes of the magnetic flux densities at the bar ends differ. One reason may be that the structural composition of the reinforcing bar has changed at the atomic level during the cutting process. The magnetization in these areas is not the same as in the remaining areas. Another reason may be that the influences of the earth magnetic field as well as those of electrical power lines are strong enough to disturb the measurements.

In addition to the unbonded reinforcing bars, three concrete specimens with predefined reinforcement layouts were casted and investigated with the MFL method. The specimens have reinforcing bars with different concrete covers, hooks, slices, crossings, broken bars and a bar with a gap.
Additionally, a bar with pitting corrosion was casted-in. The larger magnet was used to magnetize the reinforcement since the distance between the reinforcing bar and the magnet had increased.

The influence of the distance between bar and sensor were determined on the casted-in reinforcing bars as well as on the unbonded steel bar. The results of the measurements on the sliced, hooked and crossed reinforcing bars are not clear because no local extreme values are visible.

The measurements on the broken reinforcing bars (Fig. 10) show clear results. By reading the measured magnetic flux density (Fig. 11), the two breaks could be clearly identified. The measurements on the reinforcing bar which is notched with the half bar-diameter show no indication of a failure in the graphically displayed data.

The MFL method cannot be used to detect failures of reinforcing bars which are damaged by pitting corrosion either.

Since a tangible lack of information about the progression of fatigue failures in concrete structures exists, large scale tests on frames subjected to cyclic loading will be performed by another research group of the institute to investigate the load bearing behavior under service conditions.

Prior to the large-scale tests, several experiments were carried out. One of them should allow gaining experience with the magnetization, specifically on how the reinforcing bar can be magnetized as well as possible. In order to adjust the measurement setup, the reinforcement layout (Fig. 12) was taken from the frames but without encasing them.

Different types of magnets, like pot and disc magnets (Fig. 13), were investigated to find out which magnet can be used easily and which can magnetize the reinforcing bar in a way that the anomalies, (e.g. unaligned Weiss domains), are minimized.

Pot magnets have strong magnetic fields but the shapes of the streamlines are not designed to magnetize steel bars longitudinally. If disc magnets are aligned they become a large magnet with only two magnetic poles and an area of magnetic streamlines which can be used to magnetize the reinforcing bar in the longitudinal direction.

Figure 13b shows 6 disc magnets which are mounted on a piece of wood. As only the reinforcing bars in the longitudinal direction of the concrete frame are of interest, the influence of the perpendicularly aligned reinforcing bars should be reduced. The piece of wood is a brace which keeps the magnet about 70 mm away from the concrete surface.

This distance is needed to magnetize the longitudinally directed reinforcing bars and minimize the magnetization of the perpendicularly directed reinforcing bars.

A brace for the sensor made of Plexiglas was built just like for the magnet (Fig. 14). The analysis of the data recorded during different movements alongside the reinforcement layout in Figure 12 show that the distance between reinforcement and sensor is crucial.

If the perpendicularly directed reinforcing bars are slightly magnetized and the sensor has a minimum distance to the reinforcing bars, the influence of the magnetic flux emanated from the perpendicular reinforcing bars decreases.
After the preliminary experiments were done, the concrete frame (Fig. 15) was prepared for the baseline readings. Since the progression of the reinforcing bars was not visible from the surface of the specimen, they were labeled with thin pencil lines on the concrete surface (Fig. 16).

After the technical equipment was prepared, the measurements on the concrete frame were performed. Considering that the measurements were performed by a single person, they came out well. The only requirement was to guarantee free sight on the laptop because the software was controlled by an optical Bluetooth mouse 10 m far from the laptop. The measurements were carried out in the zones with tensile stresses: the corners and the midspan area. The analysis of the recorded data shows comprehensible results which are free of anomalies. The measurements at the lower middle area of the frame slab were complicated and the results are not useful because the test setup is made of steel and the distance between the truss and the concrete surface is too small.

The data analysis of these measurements will be made with Matlab since the data import can be adjusted individually for each measurement area and the results may be displayed in various ways like a three-dimensional graphic (Fig. 17) or with contour lines that illustrate the results.

3.2 Planned research

In the future research it is necessary to learn more about the physical principles to be able to compare the measured values with the physical approaches and compute mathematical functions which can be adapted to the measured values.

That will offer the possibility to look for failures such as breaks in reinforcing bars because there will be differences between the measured values and the computations.

A lot of work has been done by other researchers who are dealing with damages in prestressing steel. Investigations on the mild reinforcement are necessary because the hysteresis of reinforcing steel differs from the one of prestressing steel.

The aim of this research work is the development of an automatic working measurement system for mild reinforcement. For the detection of breaks in prestressing steel electromagnets are used to magnetize the tendons because a strong magnetic field is needed for the ferromagnetic hard material.

The mild reinforcement is made of a mild ferromagnetic material. That is why Neodymium magnets can be used for the magnetization. If the distance between the bar and the magnet increases, an electromagnet could be an option. Disadvantages compared to permanent magnets are the higher initial costs and the additional power supply. The mass of the magnet has to be considered since the measurements will be performed at vertical or overhead surfaces. So far, the MicroMag sensor is working well but it has to be calibrated. The calibration is going to be made with Helmholtz coils which generate a homogenous magnetic field inside.
The comparison between the known magnetic field and the displayed values of the sensor allows for a calibration.

A measurement resolution of 1 value per millimeter in both directions of the specimen surface is planned. Now, the measurements are performed without a positioning system for the sensor but the integration of a rotation encoder is planned. Then the measurement will be triggered by the rotation encoder when a predetermined value is achieved.

For the future research 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 with the measured values of the magnetic flux density. For the automation, other systems are needed. A rail-based system as well as a robot arm are possible options.

Further tests on predefined reinforcement layouts, including slices, hooks and crossed reinforcement, are necessary to get typical patterns of the magnetic flux density for each setting. That offers the possibility to compare the known patterns with the measured magnetic flux densities and look for differences which can be indicators for breaks in the reinforcement. For a measurement system the comparison can be done automatically. In the future the data will be processed online and displayed prospectively on a monitor. Patterns that may indicate possible breaks can be identified and the engineer in situ can perform more detailed investigations at these locations.

4 CONCLUSION AND OUTLOOK

Current non-destructive testing methods cannot provide the required information on the reinforcement or they are incomplete, costly or with a risk to human beings. The magnetic flux leakage method has the potential to detect breaks in reinforcing bars non-destructively. So far, preliminary tests on single unbroken and broken reinforcing bars have been done. Further investigations on the magnetization were carried out with Neodymium magnets on casted-in reinforcing bars. The tests showed that the magnetic field of a magnet consisting of 6 disc magnets is strong enough to magnetize the encased reinforcement. The influence of the distance between reinforcing bar and magnet or sensor was investigated on single reinforcing bars and reinforcement layouts. The results were used to adapt the distance between magnet and reinforcing bar as well as the distance between sensor and reinforcing bar.

Since the number of measuring points was limited by using an analytical measurement setup, the magnetic flux density is now measured with a 3-axis magnetometer. For the future research work the magnetometer has to be calibrated. Measurements on large-scale fatigue tests where breaks in the reinforcement are assumed to occur are planned.

The aim of the research project is the development of an automatically working measurement system. The system requires a guidance system that moves the sensors on the concrete surface. In the long term a rotation encoder will be connected to the magnetometer to assign the measured values of the magnetic flux density to the position of measuring.

With the installation of data acquisition software that can display the values three-dimensionally, real-time operations will be possible. For an automatically working measurement system a library of typical patterns in the magnetic flux density for known reinforcement setups is needed.

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6 REFERENCES