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Detection of reinforcement breaks on large-scale fatigue tests with the magnetic flux leakage method
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Abstract

Hardly any fatigue breaks of reinforcing bars in bridges have been reported so far. Presumably, this is due to the fact that fatigue breaks are not actively searched on the one hand and damages are attributed to other phenomena (e.g. corrosion) on the other. The magnetic flux leakage (MFL) method as a non-destructive testing technique offers the possibility to detect breaks of reinforcing bars. The applicability and the limits of the MFL method will be investigated in connection with large-scale fatigue tests which will be performed on reinforced concrete frames.

Preliminary tests on single unbonded steel bars and concrete specimens with predefined reinforcement layouts including breaks in the steel bars have been executed. Additional tests were performed to investigate the influence of the distance between the reinforcement and the magnet as well as the sensor. The reinforcement layouts assembled for these tests matched the layout of the specimens. The gathered results are the basis for the measurement preparation of the frame. Breaks of the reinforcement are expected to occur in the frame corners. Once a break is assumed, loading is stopped and the measurements with the MFL method are performed.

Due to the much denser reinforcement layout of large-scale specimen, the data interpretation of the measured magnetic flux values will be more complicated as in the preliminary tests. After completion of the experiment the reinforcement will be uncovered and the position of the measured breaks will be compared with the effective ones.

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 radiography with X-rays are not efficient enough to investigate larger parts of bridges under real conditions because they are costly and in the special case restricted due to the 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 inspection [4]. For the measuring of changes of the investigated structures, the technical equipment has to be installed permanently. 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 [2].

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 that changes the surrounding magnetic field considerably. Emphasis of this research is placed on the development of an automatic
measurement system, four major issues have to be studied: the physical principles of
magnetism, the investigated reinforcing steel, 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.

2.1 Physical principle

The magnetic flux density is expressed by the concentration of magnetic streamlines which
are a property of a magnetic field. The magnetic field is a vector field that shows the direction
and strength of the magnetic force at the examined position. The magnetic field of a bar
magnet is similar to the one of a magnetized reinforcing bar. In both cases the shapes of the
magnetic streamlines match very well and differ only in their strengths.

Figure 1: Magnetic field of a broken bar
magnet [2]

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” (shown as a part of Fig. 5). In contrast to the bar magnet, the
Weiss domains of a steel bar are not directed among each other and a global magnetic field
does not exist. The domains can be directed by an external magnetic field, e.g. from a
permanent magnet 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 further increase of the strength of
the external magnetic field does not lead to a stronger residual magnetization. In the hysteresis
curve of Figure 3 the magnetic saturation is labelled 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 changes every time there is contact with another magnetic field such as lifting magnets or magnetizations of former magnetic-based investigations.

When the reinforcing bar breaks or when it is mechanically processed, the Weiss domains are undirected locally and the magnetization is disturbed. Therefore previous magnetic influences have to be erased because otherwise magnetically sensitive measurements might show anomalies. A defined magnetization is achieved by repeated movements of a permanent magnet alongside the reinforcing bar (Fig. 5). 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 is finished and prior to the measurement, the external magnet has to be removed. The measurement is carried out with a MicroMag 3 Axis Magnetometer [1]. 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 (Fig. 4a). Since the flux density decreases by the power of three with the distance, the spacing between steel bar and sensor is crucial (Fig. 4b).

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.

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 larger 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 larger one of about 420 N [5]. The elementary magnets of the reinforcing bar have to be aligned by the magnetization longitudinal to the bar axis. This alignment can be achieved when the parallel part of the external magnetic field (accented with a circle) flows through the reinforcing bar (Fig. 6). The measurements with the analog Gaussmeter were to slow since the sensor had to be positioned by hand for every position of measuring, which 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 an electronically 3-axis fluxgate magnetometer (Fig. 5b) is used to measure the magnetic flux density because an automated data acquisition is needed. The magnetometer has a measurement range of ±1100 µT and a resolution of 0.015 µT which allows measuring small differences in the magnetic flux density. So far, the measurement system has no automatic positioning system but it is planned to integrate one. The position along the reinforcing bar will be temporarily measured by a rotation encoder. During the measurements the data are collected by an amplifier and stored on a computer in an ASCII format which can be read or imported by nearly all programs.

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

Tests on unbonded reinforcing bars were performed with permanent magnets and the Gaussmeter. After the magnetization with a small Neodymium magnet, measurements for different distances between sensor and steel bar were carried out. The distances varied from 16 to 46 mm. The largest absolute values belong to the distance of 16 mm and the smallest belong to the distance of 46 mm. The graphs of the measured magnetic flux densities show differences in the amplitudes at the bar ends. One reason may be that the structural composition of the reinforcing bar has changed at the atomic level during the cutting process. 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
so on. By reading the measured magnetic flux density, the breaks could be clearly identified (Fig. 6) because new local extreme values arose.

Other types of failures like pitting corrosion or notched reinforcing bars cannot be identified yet.

Large scale tests on concrete frames subjected to cyclic loading will be performed by another research group of the institute to investigate the load bearing behaviour under service conditions. Prior to the large-scale tests, several experiments were carried out. One of them should allow gaining experience with the magnetization, especially on how the reinforcing bar can be magnetized best. In order to adjust the measurement setup, the reinforcement layout was taken from the frames but without encasing them. If disc magnets are aligned they become a large magnet with only two magnetic poles and an area of parallel magnetic streamlines which can be used to magnetize the reinforcing bar in the longitudinal direction and to minimize the anomalies (e.g. unaligned Weiss domains).

After the preliminary experiments had been completed, the concrete frame was prepared for the base-line readings. Since the position of the reinforcing bars was not visible from the surface of the specimen, they were labelled with thin pencil lines on the concrete surface. Afterwards the measurements on the concrete frame were performed and they came out well. The data analysis of the 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 or with contour lines that illustrate the results.

3.2 Planned research

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

As a goal of this research work, an automatic working measurement system for the mild reinforcement will be developed. A measurement resolution of 1 value per millimetre in both directions of the specimen surface is planned. Up to now, the measurements are performed without a positioning system for the sensor but the integration of a rotation encoder is planned for the beginning of 2010. The measurement will be triggered by the rotation encoder every time when a predetermined value is achieved. For the future research an automation of the positing system that can move the sensors on the concrete surface has to be developed. A Helmholtz coil provides a defined magnetic field inside. The comparison between the known magnetic field of the coil and the displayed values of the sensor allows for a calibration.
Further tests on predefined reinforcement layouts 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 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

Current non-destructive testing methods cannot detect breaks of the reinforcement or they are incomplete, costly or with a risk to human beings. The magnetic flux leakage method has the potential to provide this information 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 on 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 analog measurement setup, the magnetic flux density is measured with a 3-axis fluxgate magnetometer which 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. 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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