Detection of reinforcement breaks

Laboratory experiments and an application of the magnetic flux leakage method

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DETECTION OF REINFORCEMENT BREAKS: LABORATORY EXPERIMENTS AND AN APPLICATION OF THE MAGNETIC FLUX LEAKAGE METHOD

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ABSTRACT

The magnetic flux leakage (MFL) method is based on the physical principle that any separation of a magnetized steel bar causes a change in the direction of the magnetic flux lines, which can be measured by induction coils. The MFL-method is therefore an appropriate basic framework to be implemented in a break detection tool.

Prior to a large-scale test, different laboratory tests were performed. These tests were used to calibrate the coils, to evaluate possible magnetization procedures and to find a repeatable technique to measure the residual magnetic field of the covered reinforcement. Another test was performed to investigate the influence of surrounding magnetic fields like the one of the earth.

A large-scale test on the fatigue behavior of small-span bridges provided the opportunity for a first practical application of the MFL-method in the laboratory. In this first run, many breaks have been detected without prior knowledge of their existence and the position. Preliminary examinations of the measured positions and the effective ones show a good correlation.

INTRODUCTION

The MFL-method can help the engineer to assess the present status of a bridge, which means in detail the state of the reinforcing bars. With respect to other NDT-methods, the MFL-method is easy to use and there are no risks for the engineer on site like the application of radiography with X-rays, which is restricted due to its potential damage to human beings (Scheel 1997). Another method, 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 time of the inspection (Vogel 2006). Compared with others methods, the MFL-method has the advantages that no earlier reference measurements are necessary and the results are roughly available during the measurement in a graphically form.

OBJECTIVES

In the last 90 years, much experience has been gained with testing materials using the MFL-method. In the US and in Germany it is used to look for breaks in prestressed tendons for over 30 years now (Scheel 2006) and since 3 years, it is applied on the break detection of reinforcing bars.

The development of an automatic break detection tool for reinforcing bars is one of the goals within the research topic. Therefore, preliminary tests were carried out to become familiar with the system and to find the optimal settings for the magnetization and measurement procedures. Measurements on different reinforcement layouts were performed to gain information about typical patterns in the measurement values. The knowledge of these patterns is essential since they form the basis for a break detection algorithm (BDA), which shall be used to detect the breaks automatically. Up to now, the analysis was done manually, which was inefficient and time-consuming.

In this paper, the typical patterns as well as the BDA will be described. The findings and measurement results of a large-scale test will be discussed and used for a run of the algorithm. The results of the analysis using the BDA will be compared with that one of the test and presented in the following sections.

MFL-METHOD

Reinforcing steel shows a magnetic behavior. A separation of a magnetized reinforcing bar into two parts leads to a new pair of magnetic poles, which can be used to detect breaks in the reinforcement. The appearance of new poles changes the surrounding magnetic field considerably, which can be measured with sensors. Prior to each measurement, the reinforcing bars have to be magnetized by an external magnetic field.

Different components, e.g. magnetic sources, sensors and the data acquisition, are needed for the automatic break detection tool. The needs were investigated and the components were chosen in the last few years. Information about the magnetic sources and sensors are described in (Wolf 2009). A more detailed explanation about the physical principle as well as the technique of magnetization can be found in (Wolf 2010). The sensor calibration as well as the data acquisition are discussed in (Fehlmann 2011).

TYPICAL PATTERNS

The MFL-method is based on the principle that the field around the poles of a steel-bar differs to that one of surrounding faultless areas. Since the relative permeability in a magnetic material ($\mu_r = 10^2 \ldots 10^6$) is much higher than in air ($1 + 0.4 \cdot 10^{-6}$), the magnetic field is striving to propagate within the material. Outside of the material, along faultless areas, the magnetic field is considerably smaller as can be seen in Fig. 1a and b. The magnetic field is represented by vector arrows, which vary on the gray scale with the strength of the field. The lighter the arrow, the smaller the field, and vice versa.

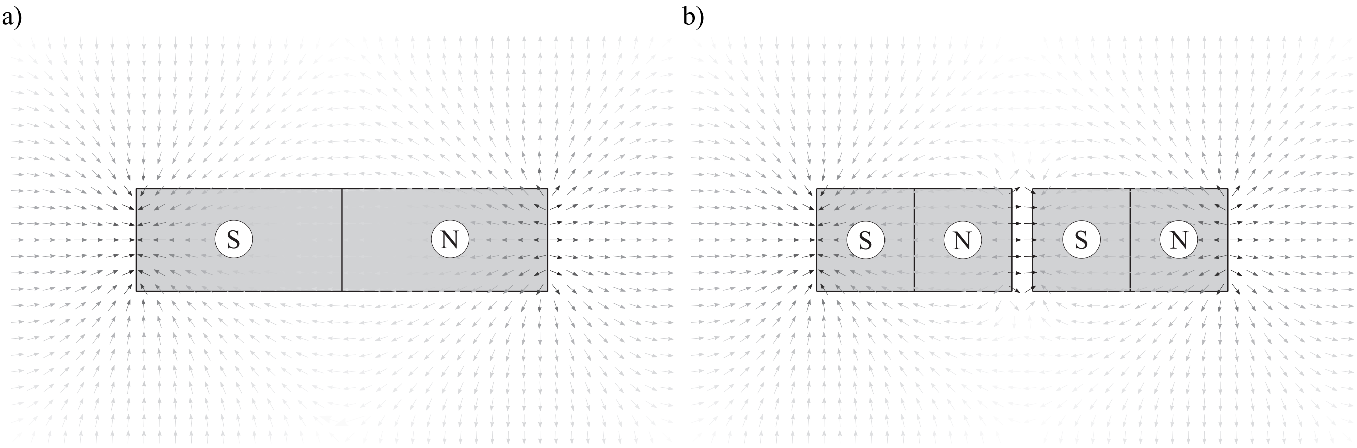

Fig. 1 Magnetic field of (a) an unbrocken and (b) a broken piece of steel (Comsol 2011).

The magnetic field was computed with the software Comsol 4.2a of Comsol AB (Stockholm). In this software, the Maxwell's equations (Equations 1 to 4) are implemented to calculate the electromagnetic fields (Leuchtmann 2005).

$$\text{rot}\,\mathbf{E}(\mathbf{r},t) = -\frac{\partial}{\partial t}\mathbf{B}(\mathbf{r},t) \tag{1}$$

$$\text{rot}\,\mathbf{H}(\mathbf{r},t) = \mathbf{J}(\mathbf{r},t) + \frac{\partial}{\partial t}\mathbf{D}(\mathbf{r},t) \tag{2}$$

$$\text{div}\,\mathbf{D}(\mathbf{r},t) = \varrho(\mathbf{r},t) \tag{3}$$

$$\text{div}\,\mathbf{B}(\mathbf{r},t) = 0 \tag{4}$$

In this research, only static magnetic fields resulting from permanent magnets are considered and there are no time-dependent processes, which simplify the equations as follows.

$$\text{rot}\,\mathbf{H}(\mathbf{r}) = \mathbf{J}(\mathbf{r}) \tag{5}$$

$$\text{div}\,\mathbf{B}(\mathbf{r}) = 0 \tag{6}$$

The magnetic field was simulated in two dimensions only since the influence of the third component can be neglected. The two components of the field are the axial and radial one. As it can be seen in Figure 1, at the position of the poles the arrows are directed towards the axis of the magnet. That means, the axial component must be zero and the radial component reaches an extreme value of the field strength at that position (Figure 2a and b).

The absolute values of the axial component increases close to the poles and decrease along the reinforcing bar until the midpoint is reached. The absolute values of the radial component are maximal at the outer poles and decreasing rapidly towards the midpoint. The sign of the axial component does not change over the whole length of the reinforcing bar and that one of the radial component switches at the midpoint.

A break of a reinforcing bar produces two ends which are magnetic poles as well. The curves of the two components differ at the break position from that one at the outer poles. A local extreme value can be found at the break position for the axial component and a zero point for the radial component. The radial component has two extreme values with different signs close to the position of the break.

a)

b)

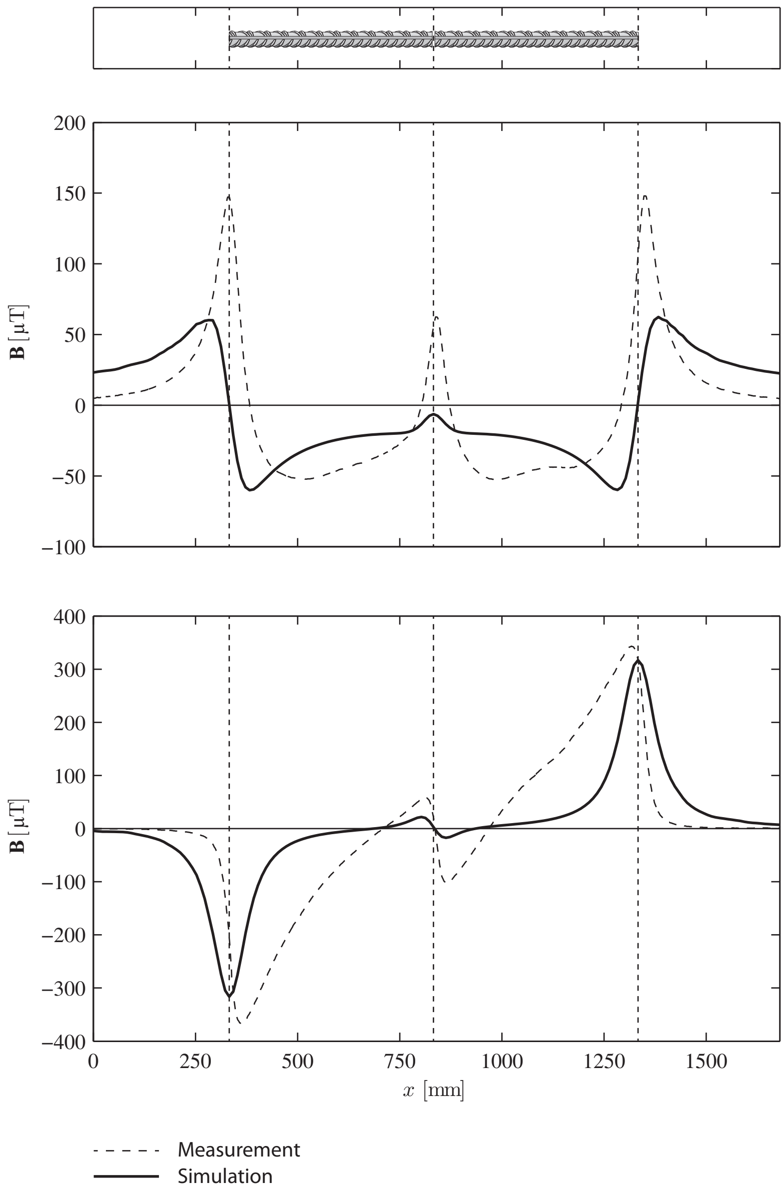

Fig. 2 Typical patterns for (a) the axial and (b) the radial component of the magnetic field of a 1 m long reinforcing bar.

BREAK DETECTION ALGORITHM

The characteristics of the break signal patterns were used to develop the BDA. The flow chart of the algorithm is shown in Fig 3. Correlations between the different positions and values are visualized in small sketches on the left hand side. The axial and radial components are always considered in the algorithm, where the consideration of the tangential component can be chosen at the beginning of the analysis.

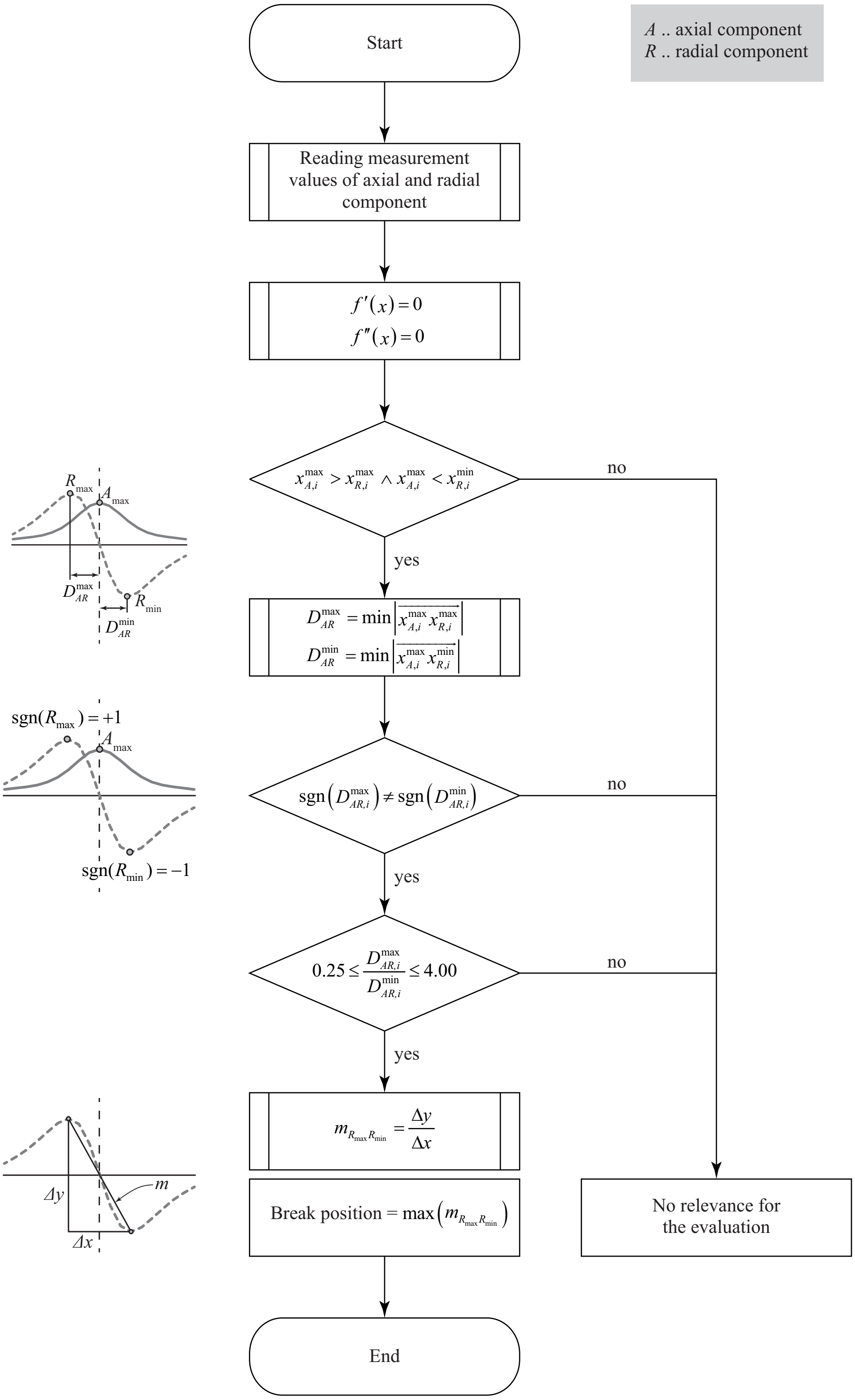

Fig. 3 Flow chart of the break detection algorithm.

Tests on different measurement series of the MFL-method show, that the BDA detects the breaks and the position of the breaks with a detection rate of about 90%. In these cases, the breaks and their positions were detected correctly. The measurement series, which were used for testing the BDA, are comparable with the one shown in Fig. 2.

LARGE SCALE TEST

Another research project in the Institute of Structural Engineering at the ETH focused on the fatigue behavior of reinforced concrete frame bridges. With this aim, data of 121 frame bridges were collected and a frame with the most frequently used configuration of concrete and reinforcement was built in the scale of 1:2. The frame was subjected to cyclic loading by a hydraulic system. More detailed information about the frame itself as well as the test procedure can be found in (Fehlmann 2011).

The cyclic loading was paused in defined intervals, where the MFL-measurements took place. The measurements were performed at the outside of the frame corners (grey areas in Fig. 4) in both, the vertical and horizontal direction. The horizontal areas were 500 mm long, the vertical ones were 700 mm high and all areas had a width of 1500 mm. At first, all reinforcing bars of the respective area were magnetized by three passes of the magnet. Then, the magnet was rotated 180° and three more passes were made, as can be seen on the left hand side in Fig. 4. As soon as the magnetization process was completed, the magnet was parked in a sufficient distance to the frame, in order to keep its magnetic field influences on the measurements as low as possible.

The measurement vehicle was positioned on the surface of the frame in a way that it could be moved along the respective reinforcing bar. The vehicle must be moved by hand since it has no motor. Because the time of one measurement is given and the distance between two measurement points has been chosen to d_{MP} = 5 mm, the vehicle cannot be moved faster than v = 5 cm/s without losing measurement points.

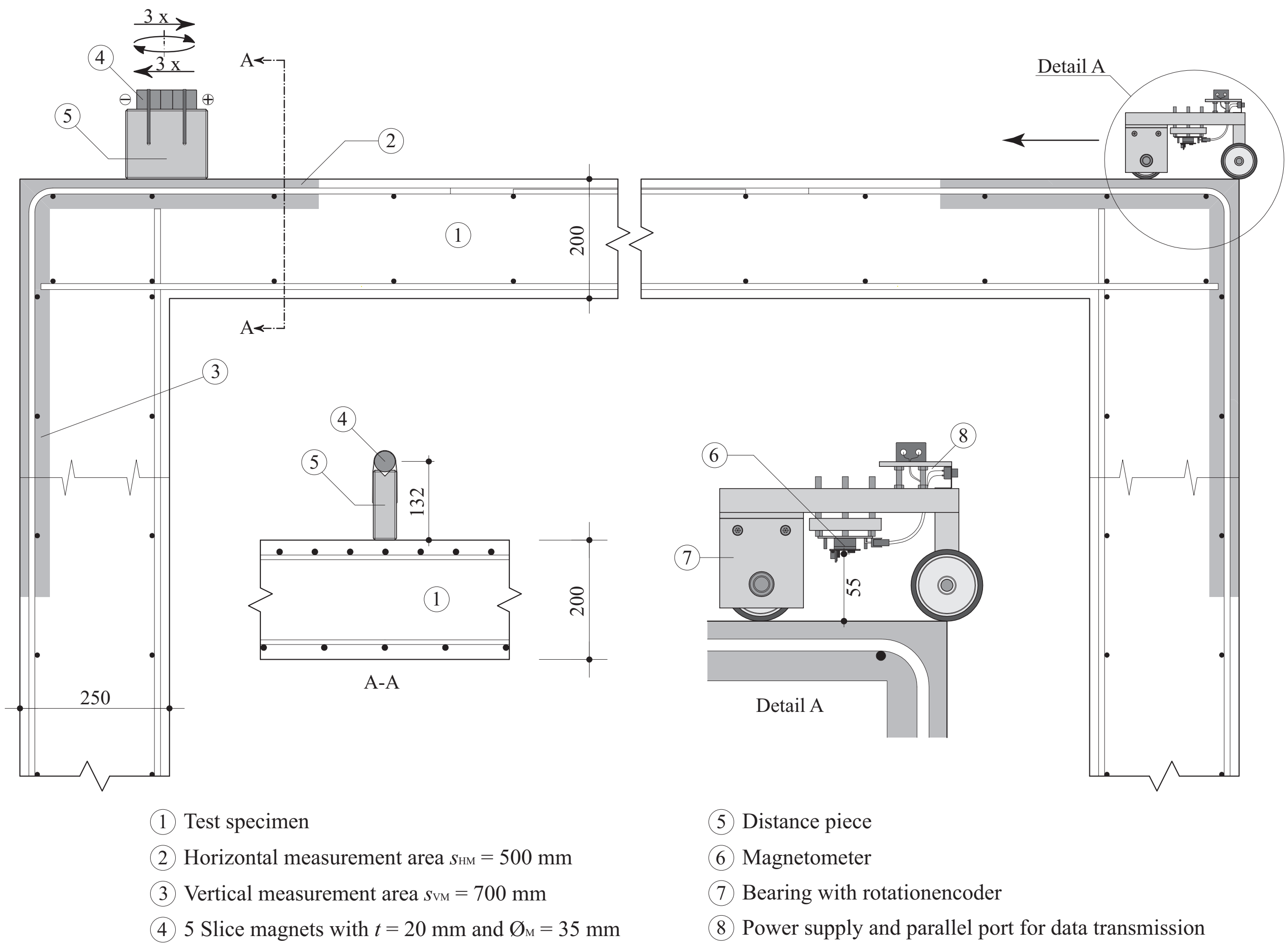

Fig. 4 Sectional drawings of the frame with magnet and measurement vehicle.

a) b)

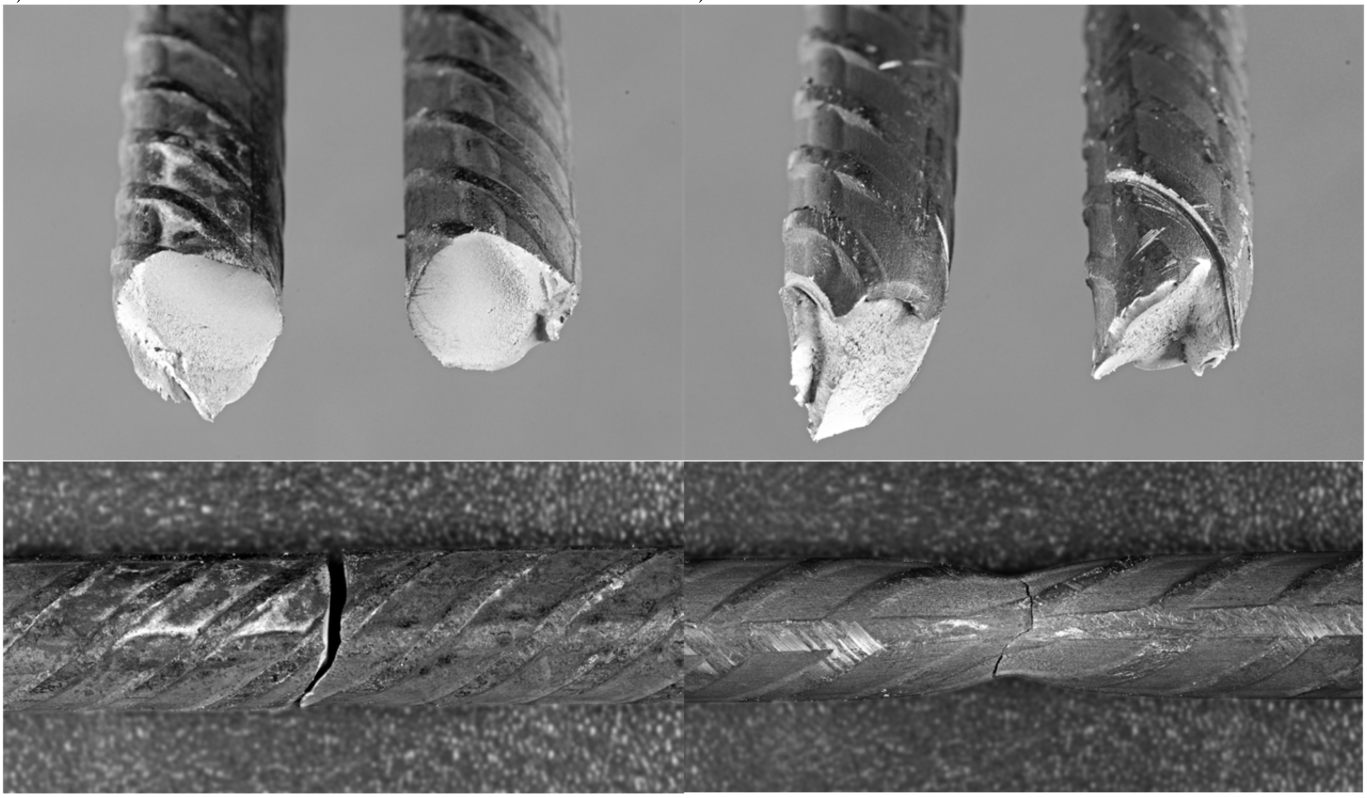

Fig. 5 Surfaces and side views of (a) a fatigue and (b) a ductile break.

The experiment on the frame was finished after 2.65 million load cycles, because the deformations of the frame increases that much, that no additional force could be applied to the frame. The concrete cover on the outer surfaces of the frame corners was removed with jackhammers. At this stage, all the bars of the top reinforcement in one of the corners (east corner) were broken. Photos of the break surfaces were taken and the breaks were classified in fatigue and ductile breaks. An example for a fatigue and a ductile break is shown in Fig. 5. The two break types have completely different break surfaces. The surfaces of the fatigue break are more or less flat and perpendicular directed to the longitudinal axis of the reinforcing bar while the ones of the ductile break are oriented in various directions and deeply ridged.

Differences in the MFL-measurements were expected since the distance between the break surfaces of the fatigue break is much larger than that one of the ductile break. The different break distances are shown in the lower part of Fig. 5.

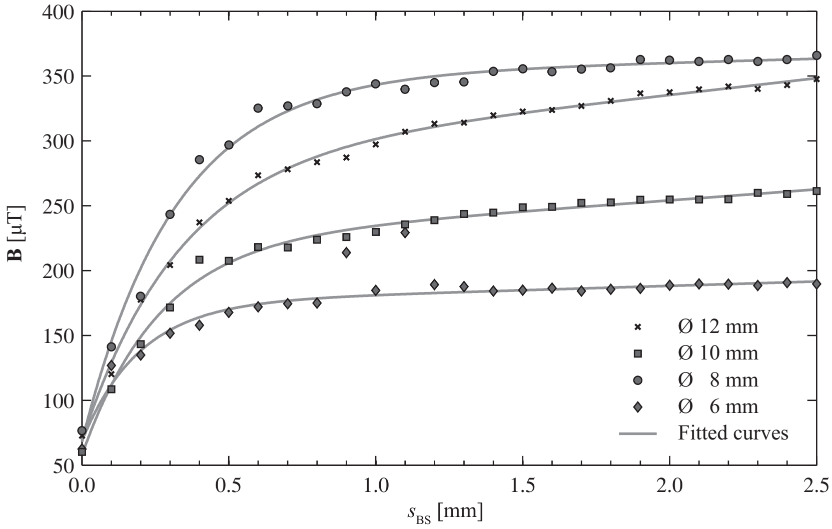

Fig. 6 Influence of the distance between break surfaces.

In this context, an experiment with broken reinforcing bars of diameters from 6 to 12 mm was performed to investigate the influence of the distance between break surfaces. The results are visualized in Fig. 6. As it can be seen, the signal strength increases with the distance until a limit value is reached. The strength increases much from 0.0 up to 1.0 mm and is more or less constant at the limit value for bigger distances. (Hillemeier 2002) got analogically results for prestressed tendons. Measurements on broken reinforcing bars with fatigue and ductile breaks confirm the results of the experiment regarding different distances between the break surfaces. The measurement values of the ductile breaks were about 4 times smaller than that ones of the fatigue breaks. Nevertheless, both break types could be detected by the MFL-method well.

DATA ANALYSIS AND APPLICATION OF BREAK DETECTION ALGORITHM

The measured values of the top reinforcement of the east frame corner were analyzed in detail since all reinforcing bars were broken. No other measurement series were considered in the further analysis, because they did not exhibited any indication of breaks.

First, the measurement values were graphically visualized and visually evaluated by hand. By combining all seven measurements at various times of the same reinforcing bar in one diagram, the evolution of breaks could be identified (see Fig. 7). The axial and radial component of the magnetic field show, at which time the reinforcing bar number 16 was broken and how the stiffness of the specimen decreased since the break distance increased. This can be concluded from the increasing strength of the field at the position of the break at $x = 238$ mm. The values of the tangential component of the magnetic field are small and vary strongly.

In a further step, the measurement values of the axial and radial component were used as input values for the BDA. The results of both, the manually analysis as well as the one of the BDA, are shown in the next section.

RESULTS

The MFL-measurements of the east frame corner were analyzed visually as well as with the BDA (see Tab. 1). The first column shows the number of the respective reinforcing bar and the second one the type of the break. The third column shows the results of the visual investigation while the fourth and fifth column shows the results of the BDA-analysis.

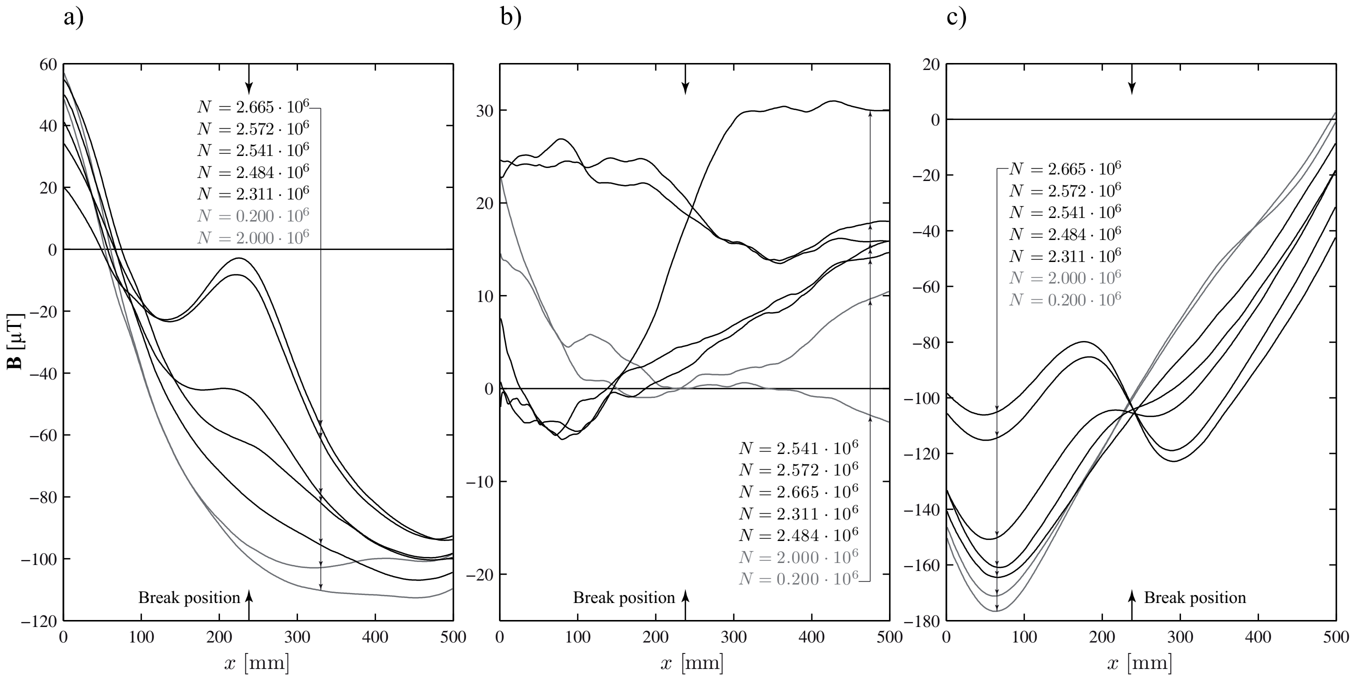

Fig. 7 Measurement curves for (a) the axial, (b) the tangential and (c) the radial component of the magnetic field.

As it can be seen, not all breaks could be detected since the measurement curves of different series show no typical break patterns. One reason could be the distance between the sensor and the reinforcing bar, which might have been too large. The influences of other equipment on the MFL-measurements are not well known up to know. Interruptions of these instruments on the magnetic sensitive measurements are possible as well.

As a result, more than 65% of the breaks could be found visually and about 50% with the BDA.

CONCLUSION

The detection performance of the MFL-method was evaluated with a large-scale test. Under controlled laboratory conditions, breaks could be detected visually and using the BDA with a high accuracy. The measurements on the reinforced concrete frame, however, have shown that the configuration of the sensors and magnets must be checked and adjusted since not all curves have shown typical break patterns. Neither the visual investigations nor the BDA of such curves were able to identify breaks.

Tab. 1 Manual and with BDA detected breaks.

Bar-N°	Break Type	Visual Detection	BDA TC = 0	BDA TC = 1
300	Fatigue	×	0	0
301	Fatigue	×	0	0
302	Fatigue	✓	0	0
303	Fatigue	✓	0	0
304	Fatigue	✓	0	0
305	Fatigue	×	1	1
306	Fatigue	×	0	0
307	Fatigue	×	0	0
308	Fatigue	×	1	1
309	Ductile	✓	0	0
310	Fatigue	×	1	1
311	Fatigue	✓	1	1
312	Ductile	-	-	-
313	Ductile	✓	0	0
314	Ductile	✓	(1)	(1)
315	Ductile	✓	(1)	0
316	Fatigue	✓	(1)	(1)
317	Fatigue	✓	(1)	(1)
318	Fatigue	✓	(1)	0
319	Fatigue	✓	(1)	1
320	Fatigue	✓	(1)	(1)
321	Fatigue	✓	1	1
322	Fatigue	✓	0	0
323	Ductile	✓	0	0
324	Fatigue	×	0	0
Summary	Σ ✓	16	-	-
	Σ ×	8	-	-
	Σ 0	-	12	14
	Σ 1	-	5	6
	Σ (1)	-	7	4

✓	visible
×	not visible
0	not detected
1	detected
(1)	detected beside the real position
TC	tangential component

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