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Detection of reinforcement bar fractures by measuring the remanent and active magnetic field

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Abstract
The magnetic flux leakage method enables the detection of reinforcement bar fractures, resulting from fatigue or high tensile loading, as they may occur in bridges. An experimental measuring device was developed in a preceding project for laboratory application, enabling the evaluation of single reinforcement bars. The aim is to establish a surface measurement, which simplifies the detection of reinforcing steel breaks in cases where the exact position of the bars is unknown. The extended measurement range will provide more information about the test object, such that new criteria to evaluate the condition of the reinforcement can be developed. Alternatively to the assessment by remanent magnetisation, measurements can be made using active magnetic fields. This method will be improved in terms of measurement width, depth, velocity and handling, in order to develop a hand-held device for practical application.

1 Introduction
The magnetic flux leakage method is one of the oldest non-destructive testing methods. It is commonly applied in the mass-production of semi-finished products, however, it has not been commercially implemented in the discipline of civil engineering.

Valuable scientific contributions have been made in this field, starting with the investigations of Kusenberger and Barton [1] in the 70s and 80s, where several non-destructive testing methods for the detection of fractures of prestressed reinforcement were evaluated. The magnetic flux leakage method proved to be the most promising of all fifteen testing methods evaluated.

The method was refined by Scheel [2] in the 90s. Scheel found characteristic curves by performing further experiments and also provided an interpretation from a physical background. A large-scale measuring device was developed, based on Scheel’s research at TU Berlin, by equipping a car trailer with an electromagnet and a rotating array of hall sensors [3], [4], [5]. The primary focus was on the prestressed reinforcement whereas the conventional non-prestressed reinforcement was seen as a disturbing signal. Measures were taken to reduce those signals.

Wolf [6] successfully applied the method to non-prestressed reinforcement for the non-destructive testing of large-scale fatigue tests. A handheld device was developed, which was capable of remanent field measurement.

2 Procedure of magnetisation and measurement
The procedure of remanent field measurement and measurement in an active magnetic field is shown in Fig. 1 a-c and Fig. 1 d, respectively.

A reinforcement bar with a fracture, due to fatigue action or large deformation, is illustrated in Fig. 1 a. The method does not require a crack width between both fracture surfaces to function, however, the reliability improves with increasing crack width.

Steel bars can be magnetised irregularly due to the production process or transportation with a lifting magnet. In order to ensure a regular magnetisation, the bar has to be magnetised to the saturation point of the material over the entire length. This can be achieved by moving a permanent magnet along the reinforcement bar. The permanent magnet produces a strong magnetic field around itself which could induce a magnetisation in the bar, when moved along the bar length, opposite to direction of its own magnetisation. This phenomenon is illustrated by small magnets around the bar.
The bar retains a residual magnetisation and behaves like a long, weak permanent magnet (Fig. 1 b), after the magnetisation process. This is called remanent magnetisation. At the fracture position, the propagation of magnetic flux is obstructed by the discontinuity in the material. A much smaller magnetic permeability of the surrounding concrete and air relative to the steel causes the magnetic flux to occupy a larger volume around the fracture to propagate from one fracture plane to the other. This rather figurative explanation of the phenomenon led to the name magnetic flux leakage method.

The stray field of the “leaking out” magnetic flux can be detected by a suitable measuring device (Fig. 1 c) at a distance in the range of the typical concrete cover.

So far the process has been described as it was developed and implemented in the preceding project by Wolf [6] at the ETH Zurich. Subsequently, the existing measuring device was equipped with an iron core and two coils (Fig. 1 d) in order to enable magnetisation and measurement in a single step. This process, in contrast to the remanent field measurement, is called active field measurement. The mentioned enhancement of the existing device is merely an intermediate step towards the development of a new device.

The unification of magnetisation and measurement in a single step is just one advantage of the active field measurement. Similar to tests by Walther [7], experiments and simulations performed by the author confirm a distinct enhancement of the measurement depth. The active measurement provides sharper signals, as the higher signal amplitude stands for higher signal strength and the smaller signal width simplifies the location of the signal source.

3 Signal interpretation and representation

3.1 Measurement along a straight line

A cylindrical permanent magnet with its typical magnetic field is shown in Fig. 2. The orientation of the field in the plane of projection is represented by arrows. This magnet is comparable to a magnetised reinforcement bar. A non-destructive testing method cannot capture the entire field and is limited to that part of the field which is accessible without disrupting the concrete cover. In this example, the three components of the magnetic field are measured along a straight line above the reinforcement bar and are represented by three curves. These curves correspond to the orientation of the arrows and contain information on the magnitude of the magnetic field.

The y-value remains zero directly above the bar as there is no field perpendicular to the plane of projection. The x- and z-curves, however, indicate distinctive patterns at the bar ends. The vertical component of the magnetic field shows an extreme value at each bar end, which leads to a local minimum and a local maximum in the z-direction. The reversal in the horizontal magnetic field component leads to a zero-crossing of the x-direction.
The signals apply to the depicted magnet with the north pole to the right and the direction of measurement from left to the right. Reversal of either the magnet or the direction of measurement leads to an inversion of the measured field directions.

A fracture signal for known bar end signals is comparable to the superposition of two bars separated by a small gap, as shown in Fig. 3. This superposition results in a fracture signal consisting of a local maximum of the $x$-component and a zero-crossing from plus to minus in the $z$-component. A reversal point at the fracture position is observed again.

The principle of superposition is only applicable to linear systems in a purely theoretical sense. The ferromagnetic magnetisation is not a linear process, however, a good approximation for remanent magnetisation problems is obtained, as long as the magnetisation is carried out to saturation point throughout the probe.

This simple experimental setup provides sufficient information for the reliable break detection in cases where the reinforcement layout is relatively uniform.

![Fig. 2](image1.png)

**Fig. 2** Signal at the bar ends on the example of a permanent magnet

### 3.2 Two-dimensional measurement

![Fig. 3](image2.png)

**Fig. 3** Fracture signal obtained from the superposition of two bars separated by a signal gap.

The measurement of single bars, as developed by Wolf [6], was suitable for laboratory application and provided valuable results regarding typical bar signals, fracture signals and disturbance signals. Application on real structures, however, requires a different approach. Performing measurements directly above a reinforcement bar is too costly for use in practice. Typical tolerances on the placement of the reinforcement may be negligible for its static purpose. The measurement, however, will
be affected significantly. The localisation and marking of the exact reinforcement bar position prior to the measurement is time consuming and not feasible for commercial use.

Therefore, it is sensible to perform the measurement on a plane which has to be at least wide enough to cover the inaccuracies in the distribution of the reinforcement. Ideally, this measurement width will cover several bars simultaneously.

Fig. 4 Emulating a two-dimensional measurement with the existing device: (a) experimental setup; (b) measuring device; (c) representation of the three components of the measured magnetic field

The experimental setup of a wooden frame holding the longitudinal and transverse reinforcement is shown in Fig. 4 a. One longitudinal bar has a fracture, as illustrated in the detail. The fracture surfaces are restrained from moving apart by means of a flexible tube. A plane measurement was emulated with the existing device by conducting several linear measurements, which were offset laterally in steps of one centimetre. The measurements covered the width of three longitudinal bars and were conducted in an active field. The adapted device, allowing magnetisation, is shown in Fig. 4 b. The magnetic field strength of all three components is represented in shades of grey in Fig. 4 c. The figure contrast was enhanced with an algorithm. It was found that the position of the three longitudinal bars in the measurement range could not be identified from the measurements, because their signals were found to merge into one another. Distinct disturbing signals were observed at all seven transversal bars, which could allow the engineer to recognise the positions of the transversal reinforcement. The
fracture signal, however, can be distinguished from these disturbing signals as they are strongly localised and prominently visible in all three components.

The plane measurement provides information in an additional dimension in comparison to the measurement on a single line. The y-component, originally providing a zero measurement directly above the bar, now gives valuable information when it is captured lateral to the bar.

4 Further steps

Following the development of the new device, typical arrangements of reinforcing steel will be evaluated with increasing complexity. The signals will be analysed and interpreted in order to determine their typical magnetic signature and to distinguish between undamaged regions and bar fractures.

The evaluation of the results will be based on purely mathematical formulations as well as image enhancement algorithms, which will enable the trained engineer the evaluation of the structural condition. Furthermore, the reliability and accuracy of the method will be investigated.

The suitability for practical application will be investigated on large-scale fatigue experiments and real building structures.

References


