

First Applications on the Detection of Fatigue Breaks in Bridges with the Magnetic Flux Leakage Method

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ABSTRACT: Recently, discussions about heavier trucks and railway cars have re-established the discussion about fatigue behavior of reinforced concrete bridges. The paper briefly describes large-scale fatigue tests on reinforced concrete frame bridges. Special attention is paid on monitoring of the expected steel bar breaks by non-destructive testing, in particular by the magnetic flux leakage (MFL) method.

1 INTRODUCTION

Compared to other building materials, there is a great lack of knowledge in the domain of fatigue in reinforced concrete. In structural steel, methods based on fracture mechanics have been successfully applied for many years. The residual service life of a steel bridge with existing fatigue damages can be calculated as a function of the fatigue crack growth. However, such methods do not work for the assessment of concrete bridges because the surface of the reinforcement is not visible and cracks in reinforcing bars can neither be detected nor measured.

The magnetic flux leakage (MFL) method offers the possibility to detect breaks of covered reinforcing bars non-destructively up to a concrete cover of 100 mm. In this paper, the applicability and the limits of the MFL method will be discussed based on its application at the large-scale tests described.

With long-span concrete bridges the ratio of frequent live loads to dead loads is small. With small-span frame bridges, however, the effects of traffic loads reach a considerable level compared to that one of the dead loads. Thus, traffic loads are causing large stress variations in the members and therefore, fatigue becomes an issue for these bridges, Pimentel *et al.* (2008).

To clarify the load-bearing behavior under service conditions, large-scale tests on frame structures under cyclic loading are performed. The specimens on a scale of 1:2 are designed to match dimensions and detailing of common short-span bridges on Swiss motorways built in the 1960s and 1970s.

Since the MFL method is not suitable for permanent measuring, acoustic emission (AE) analysis was chosen for long-term monitoring of the specimen. The AE analysis has the advantage that changes of the condition over a certain time period can be measured, Vogel *et al.* (2006). The MFL method extends the existing tools with the possibility to assess the condition of the reinforcement. The combination of both methods is reasonable and powerful. The investigations in the field of the MFL method are devided into the following items: the physical principles of magnetism, the reinforcing steel type, the technical measurement equipment as well as the data acquisition and analysis.



The information gathered from the measurements with the MFL method on the laboratory tests will be used to develop a measurement system to magnetize, measure and look for breaks in a convenient way.

2 LARGE SCALE TESTS

2.1 Specimens and test setup

In a preliminary investigation, 121 frame bridges of the Swiss highway network have been collected to choose appropriate dimensions and structural detailing for the specimen. As frame bridges carry loads mainly in their longitudinal direction, only a strip of the bridge is modeled with the specimen. The width of the frame is 1.5 m which corresponds to a 3.0 m wide segment of a real bridge i.e. one traffic lane. For all the examined bridges, so called Torsteel which is cold-formed by twisting was used for the reinforcement. Later generations of Torsteel show higher elastic limits and tensile strengths than the first generations but the characteristic of the stress-strain-relationship always remains the same. As a result, a hot-rolled coiled steel has been chosen for the specimens. The stress-strain-relationship of this steel is very similar to the one of Torsteel.

The footings of the frame are fixed to the strong floor. Two single loads are applied by 400 kN actuators and distributed over the whole width of the specimen by stiff steel girders. The test setup (see Fig. 1) also allows the performance of a static test after the dynamic testing to determine the residual loading capacity of the specimen.



Figure 1. Scheme of the test setup. Dimensions in mm.



2.2 Test procedure

The test procedure includes continuous gaging under cyclic loading as well as periodical measurements under static loading. Deflections, strains, crack widths and loads are recorded continuously by linear variable differential transformers (LVDT) and load cells. Reinforcement strains are measured by strain gages which are applied on the surface of five bars. Periodical measurements include 706 demountable deformeter readings, detailed measurement of crack widths, marking of new cracks and taking photos. Additionally, AE analysis and the MFL method are used with a focus on the condition of the reinforcement. With the duration of the test, the number of load cycles between two measurement cycles will be extended. Until now, periodical measurements have been performed after 0, 1, 50.000, 200.000, 500.000 and 1 million load cycles. Measurements with the MFL method were carried out prior to the first cyclic loading step. In the case of irregularities e.g. a sudden increase of deflections or a high number of signals in the AE measurements, the loading procedure is suspended and an additional measurement cycle is performed. The test procedure and the applied loads can be seen in Figure 2. The upper load of 120 kN corresponds to 40% of the ultimate load.



Figure 2. Test procedure.

2.3 Results and expectations

Figure 3a shows the measured reinforcement stresses during cyclic loading. Stress differences vary from approximately 150 N/mm² in midfield (bottom reinforcement) to 220 N/mm² in the frame corners (top reinforcement). Figure 3b shows test data of two series of fatigue tests with uncovered (naked) reinforcing bars. The first series with Steel IIIa and IIIb has been carried out by Fernández Canteli *et al.* (1984) and the second one with current brands of reinforcing steel by Fehlmann & Vogel (2009). The brand used for the specimens is *topar-R* and has been tested in the second series. Assuming a similar behavior of the specimen's reinforcement and the naked reinforcing bars, the first damages in single reinforcing bars can be expected at approximately $2.4 \cdot 10^6$ load cycles. Consequently, monitoring with AE and MFL method is intensified after 2 million load cycles.





Figure 3a. Reinforcement stress differences measured in the test during cyclic loading (left). 3b. Fatigue test results of naked reinforcing steels (right), Fehlmann & Vogel (2009), Fernández Canteli *et al.* (1984), SIA 262 Concrete Structures (2003).

3 MAGNETIC FLUX LEAKAGE METHOD

3.1 Physical background

The MFL method uses the fact that a permanent magnet divided into two parts leads to a new pair of magnetic poles that changes the surrounding magnetic field considerably, Scheel (1997). The magnetic field of a magnetized reinforcing bar is similar to the one of a bar magnet. In both cases the shapes of the magnetic streamlines match very well and differ only in intensity.

The magnetic field can be illustrated by a representation which shows the direction and intensity of the magnetic force at the examined position. Details on the magnetic field in particular the magnetic force can be gathered by measuring the magnetic flux density which stands for the concentration of the magnetic streamlines. A new pair of poles leads to a change of the direction of the streamlines.



Figure 4. Magnetic field flowing through a steel bar and redirection of the Weiss domains (based on Tipler & Mosca (2004)).



Local extrema in the component parallel to the bar arise at the position of a break. Both, the extrema and the change of the direction are interpreted as a break signal pattern.

At the atomic level the bar magnet is composed of elementary dipoles with small magnetic fields all having the same direction. The bar magnet has a strong surrounding magnetic field since all dipoles are aligned parallel to each other. The material of a steel bar is also composed of elementary magnets but in most cases without a significant magnetic field. During the cooling process of the steel, different so-called "Weiss domains" with equal direction of elementary magnets are formed. (Fig. 4). In contrast to a magnet, the Weiss domains of a steel bar are oriented in various directions in a way that no global magnetic field exists. The domains can be redirected by an external magnetic field, however, resulting in a strong residual magnetic field surrounding the steel bar.

3.2 Technical equipment

The procedure can be divided into four steps: magnetization, positioning, measurement and data acquisition.

The magnetization leads to the adaption of the Weiss domains. An external magnetic field is necessary for the magnetization of the investigated reinforcement. In the testing, a permanent Neodymium-iron-boron magnet is used which consists of an Nd2Fe14B-alloy. This alloy has a strong magnetic field compared to its weight. With a diameter of 35 mm and a total length of 120 mm, the magnet is easy to handle.

A rotation encoder connects the measurements of the magnetometer with the actual position. The encoder triggers the measurement of the magnetic flux density after it has reached a preset distance. After first experiences with an analogical measurement equipment, Wolf & Vogel (2010), an electronically 3-axis fluxgate magnetometer (Fig. 5a) of PNI SENSOR-CORPORATION (2009) is used. This device has a measurement range of \pm 1100 µT and allows measuring small differences in the magnetic flux density.



Figure 5a. MicroMag 3-axis magnetometer. 5b. Measurement vehicle with rotation encoder and magnetometer.

A specially designed measurement vehicle (Fig. 5b) connects the magnetometer and the rotation encoder. With regard to the magnetic sensitive measurements, the vehicle contains only aluminum, plastic and brass but no steel. As shown in Figure 5b, the rotation encoder is connected to the front wheel. The magnetometer is mounted below the main plate and can be



adjusted in height. For the data acquisition, special software routine was written in LabVIEW provided by National Instruments, since there was no ready-made application available. The device drivers for the rotation encoder and the magnetometer are also programmed in LabVIEW and integrated into the acquisition code. The graphic user interface allows the input of relevant information. Diagrams show the actual position as well as the stereoscopic measurement readings of the magnetic flux density. The diagrams offer the possibility to check for breaks immediately and on-site. The measurement is saved in real-time using a binary format. Once a measurement is completed it is saved in an ASCII format as well.

3.3 Technique of magnetization and measurement

Once a reinforcing bar is produced, it has a magnetic history. Its magnetic field changes every time the bar either comes into contact with a magnetic field, is mechanically processed or breaks. With regard to magnetically sensitive measurements, the previous magnetic influences have to be erased and a defined magnetization has to be achieved. The elementary magnets of the reinforcing bar have to be aligned longitudinally to the bar axis (in Fig. 4 highlighted with a circle). This can be done with a magnet by repeated movements alongside the reinforcing bar. The Weiss domains adapt their magnetic orientation to the one of the external magnetic field. Since the flux density decreases by the power of three with the distance a specific distance between the magnet and the reinforcing bar is necessary, Leuchtmann (2005). Influences of the transverse reinforcement can be minimized because the distance is too large for magnetizing this direction.

After the magnetization but prior to the measurements, the external magnet has to be removed and the magnetometer can be positioned. To measure the magnetic flux density of the residual field the magnetometer has to be moved with a specific distance alongside the reinforcing bar and all three components of the magnetic field can be recorded.

4 EXPERIMENT

4.1 *Preliminary tests and preparations*

Preliminary tests were performed on single uncovered intact reinforcing bars as well as on broken ones. Measurements were also carried out on small concrete slabs with variations of the concrete cover and the type of damage. Hooked and spliced reinforcing bars were casted-in as well. Detailed information can be found in Wolf & Vogel (2009). Additional tests were performed with the same uncovered reinforcement layout as used in the reinforced concrete frame.

With the preliminary tests, the optimal distance between reinforcing bar and magnet was determined. However, this determined distance can only be used for this particular magnet. Additional experiments and calculations for other magnets have yet to be made.

Small tests and the calibration of the magnetometer were performed prior to the main experiment. The calibration was necessary since the knowledge about the absolute values of the magnetic flux density is needed for subtracting the surrounding magnetic field from the measurement readings.

A Helmholtz coil was used for the calibration, because it has a static magnetic field with a well known density of the magnetic flux density inside. The outputs of the magnetometer can be correlated with the magnetic flux. Calibration functions were determined for different sampling rates of the magnetometer. The functions are used to convert the measurement readings.



The layout of the longitudinal bars in the frame corners was marked with thin pencil lines on the concrete surface. Thus, magnetization can be performed effective and fast.

4.2 Experiment

The initial readings with the MFL method had to be performed prior to the large-scale test, because afterwards the frame was completely instrumented. The first measurements were carried out only with the magnetometer because the test vehicle was not yet ready. That is why the measurement readings were gained without the respective position of the sensors. After 50.000 cycles a second initial reading was performed, this time with the vehicle and the position details. As shown in Figure 1, only the outer sides of the frame corners are investigated with the MFL method since in these areas the largest stress amplitudes in the reinforcing bars occur.

The next measurements are planned to be taken during periodic measurement cycles. Additional measurements will be necessary when irregularities emerge.

In the first trial, only one reinforcing bar was magnetized and then the measurement was performed. Since the neighboring reinforcing bar was not magnetized, the influences of its magnetic history were large enough to disturb the measurements. In the second trial, all reinforcing bar were magnetized prior to the measurements. No disturbing signals were recorded with this procedure.

The measurement readings were analyzed with Matlab. A script to import the measured data, to convert it and to prepare it for 3D visualization (Fig. 6) was written.



Figure 6a. Visualized measurement readings of rebar 5 including a break signal pattern. 6b. Stereoscopic visualization of the measurements on a reinforcement layout including 4 break signal patterns (labeled with circles).

In Figure 6a, the measurement readings of one rebar are visualized. The three components of the magnetic field are shown as well as the absolute value computed from the parallel and radial component of the magnetic flux density. One typical break signal pattern can be seen at the position of x = 1107 mm. Figure 6b shows the measurements on the same reinforcement layout as casted-in in the reinforced concrete frame. It consists of 6 reinforcing bars. The black lines in the 3D surface represent the measurement readings along the reinforcing bars while the circles label the break signal patterns.

The 3D surface can give an overview for the engineer on the condition of the reinforcement regarding breaks. If breaks are assumed based on the 3D surface, the engineer can analyze the 2D plots which are slices of the 3D surface.



Until now, no typical break signal patterns could be found in the measurement readings of the concrete frame. If breaks in the reinforcement of the concrete frame will occur, the research group has tools to detect them easily.

5 CONCLUSIONS

Present structural concrete codes propose a method to calculate the fatigue life of the reinforcement which is easy to apply and therefore mainly interesting for practical engineers designing new bridges. The application of this method for the assessment of existing bridges is very limited, however, because assumptions of the stress history have to be made.

It is thus necessary to find out more about the fatigue damage mechanisms in reinforced concrete and to explore or adapt methods which enable the detection of endangered or already damaged bridges. With the experimental investigations presented in this paper the authors have tried to cover the latter of these two domains. A combination of non-destructive testing methods is applied under laboratory conditions. The acoustic emission analysis is used to detect possible breaks. The MFL method which is still under development shall help to localize the damages in the reinforcement. The findings from the tests will help to improve the application of the MFL method and to adjust the measurement equipment.

The final goal is to develop a powerful tool to assess existing concrete bridges providing the engineer with information on the fatigue condition of the reinforcement.

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