Magnetoelastic stress measurement and material defect detection in prestressed tendons using coil sensors

Hans-Joachim WICHMANN¹, Alexander HOLST¹, Harald BUDELMANN¹

¹ Institute for Building Materials, Concrete Construction and Fire Protection (iBMB), University of Braunschweig, Germany, h.wichmann@tu-braunschweig.de

Abstract

Apart from the general state of the tendon the quantity of the stress in the prestressed steel is of prime importance for the safety assessment of prestressed structures and/or anchor systems. On account of precaution reasons it was necessary to create a reliable, sturdy and competitive measuring device for the direct stress monitoring in prestressing steel elements being used in sensitive infrastructure buildings and other building structures subjected to high demands as e.g. bridges.

Within the framework of the Collaborative Research Center (CRC) 477 at the Technical University of Braunschweig the magnetoelastic method has been used for the stress measurement in prestressed trial members as well as in experimental and real structures. Extensive investigations showed the suitability, long-term performance and stability of the measuring principle. Magnetoelastic coil sensors in various sizes fit to different types of prestressed steel were developed. Up to now, magnetoelastic coil sensors were applied in several motorway bridges, at ground anchors and at the trial bridge “Concerto” as well as at prestressed masonry wall elements to supervise the stress in the tendons over a longer time span. Further investigations using coil sensors to detect material defects and corrosion will be discussed and explained as well.

Résumé

Dans le cadre de l'unité de recherches interdisciplinaires 477 (SFB477) à l'université technique de Braunschweig, la méthode magnéto-élastique a été employée pour mesurer les contraintes dans les éprouvettes précontraintes aussi bien que dans les structures expérimentales ou réelles. Des investigations étendues ont montré l'utilité ainsi que la performance et la stabilité à long terme du principe de mesure. Des capteurs bobines magnéto-élastiques de diverses tailles, adaptés à différents types d'acier précontraint, ont été développés. Jusqu'ici, des capteurs bobines magnéto-élastiques ont été montés dans plusieurs ponts d'autoroute, sur les systèmes d'ancrage et dans le pont expérimental « concerto » aussi bien que sur des éléments précontraints de mur en maçonnerie pour surveiller les contraintes dans les câbles de précontrainte pendant une plus longue période. Des investigations utilisant des capteurs bobines pour détecter les défauts des matériaux et la corrosion font tout aussi l'objet d'une discussion et d'une explication.

Keywords

Monitoring, NDT, force measurement, quality control, bridges

1 Introduction

The magnetoelastic effect indicates the interaction between the mechanical and the magnetic properties of ferromagnetic materials. When stressing ferromagnetic materials their magnetic properties change as well. If an alternating magnetic field is applied to a ferromagnetic material, its magnetization will trace out a loop called a hysteresis loop. Fig. 1
shows the hysteresis loop under impact of tensile stress. With increasing stress the hysteresis loop is more flattopped, the gradient of the hysteresis loop decreases. Several typical magnetic characteristics can be obtained from the hysteresis loop (see Fig. 1).

![Figure 1. Changes of the magnetic hysteresis loop of steel, exposed to tensile stress with specification of the describing parameters of the magnetic hysteresis loop](image)

Since the 1970s, stress measurement using the magnetoelastic effect were made i.e. at the Universities of Bratislava (Slovakia) and Osaka [1]. In these investigations, only the magnetic permeability $\mu_r$ was used to determine the stress. By measuring four magnetic characteristics all at once it is possible to determine the stress even in such steels (i.e. hot rolled steels with a high Si-content), whose measuring results are ambiguous when only one magnetic characteristic is measured [2].

### 2 Measuring principle and sensors

Fig. 2 shows the fundamental test assembly. In this case one coil is used to excite the magnetic field and another outer coil is used to create the induced voltage. A prestressed wire or strand takes over the function of the core of the coil. A sine-shaped alternating current $I_{err}$ is fed into the operating winding from the regulated generator $G$ and the induced voltage $U_i$ in the induction coil is gauged.

![Figure 2. Test assembly for the measurement of magnetic characteristics](image)

A continuous follow-up of the induced voltage $U_i$ and of the exciting current $I_{err}$ allows it to calculate the magnetic characteristics of the prestressed steel. The usage of a regulated source of current has made it possible to reduce the dimensions of the sensor to a minimum size without a loss of accuracy.

Fig. 3 shows a cross-section of the cylindrical sensor. On a plastic bobbin the induction and operating windings are coiled. The induction coil is smaller than and completely enclosed by the operating winding. The cylindrical sensor is mounted by being slipped over the
prestressed wire or strand, which means that it can only be applied when mounted during construction. To achieve exact results an initial calibration of the sensor on the steel type is necessary. Magnetoelastic sensors in various sizes fit to different types of prestressed steel were developed. Since the sensors are comparatively small they can be mounted in places where other sensors due to their size and complexity cannot be used. Unlike strain gauges the coil sensors are also applicable on prestressed strands and ribbons. A good long-term stability during the lifetime of the construction and an absolute measuring accuracy of ca. 30 MPa can be expected. The mounting procedure is easy. The sensor is simply pushed onto the tendon.

Also a subsequent installation on site onto external tendons is possible. Here the coils have to be spooled manually onto the tendon. Fig. 4 shows the assembly of that sensor type on site. Two semi-bobbins are connected on the prestressed wire or strand. By rotating the bobbin the induction coil and subsequently the operating winding are coiled onto the bobbin.

The block diagram of the new measurement device is displayed in Fig. 5. It allows the dynamic measurement of two selected of up to 24 channels or static measurement of all 24 channels.

3 Force measurement on prestressed masonry wall elements

In 2005, a new industrial building was built in the Braunschweig Civil Engineering Material Testing Institute. In the prestressed walls of the building, made of sand lime bricks, magnetoelastic coil sensors were installed on all 19 tendons. Fig. 6 shows the anchor head of
a monostrand with the test plug to connect the measurement device (left) and one of the prestressed wall elements (right).

![Figure 6. Anchor head of a monostrand with test plug (left) and one of the prestressed wall elements (to the right)](image)

![Figure 7. Strands in a prestressed sand lime brick wall)](image)

Fig. 7 shows the stress gradient in the prestressed elements in one wall. All elements were prestressed in the range from 158–178 kN. In the time span of the first 600 days after prestressing, the stress in the elements declined with 14 kN, mainly in the first months. Due to the later decelerated decline, a temporary process influenced by settlement and shrinkage can be assumed.

4 Box girder bridges with external tendons

In order to determine the stress in the tendons magnetoelastic coil sensors were mounted in several box girder bridges in Germany. Most of the sensors were coiled at site. Fig. 8 shows the inner view of one of these bridges, Fig. 9 a mounted coil sensor on a tendon.

![Figure 8. Box girder bridge](image)

![Figure 9. Mounted coil sensor](image)

Fig. 10 shows the changes of the magnetic parameters while a tendon was prestressed. The results are standardized to obtain a better comparability. The tendons consist of several cold drawn wires or strands. Using this type of tendons, with increasing stress a continuous decrease of the magnetic parameters is determined, compare also Fig. 1. Unlike i.e. load cells, stress measurement at all positions along the course of the tendon is possible with magnetoelastic coil sensors. Stress measurement at one position only is not always sufficient.

Fig. 11 shows the stress in one of the prestressed elements measured using coil sensors just behind the pulling anchor and in front of the holding anchor as well as the loss of stress between the pulling and the holding anchor due to friction.
The measured friction losses increases with increasing stress from 9% to 31%, which correlates with the calculated losses of about 29%.

5 Magnetic parameters under influence of corrosion, surface defects and plastic deformation

Another task of this project was whether corrosion or surface defects on prestressed elements could be detected using coil sensors. Corrosion changes the material properties and the diameter of a prestressed element and as a result of this, the stress distribution and magnetic parameters as well.

Several different wires and strands were initially damaged with surface defects of different length, form and depth. A coil sensor was placed in different positions in front of, above and behind the surface defects. The strands were tested with loads from 0°kN to 150°kN, the wires with loads from 0°kN to 120°kN. The two following figures show the percental changes of the magnetic parameters for a local corroded monostrand at a load of 150°kN. The frequency of the excitation current was f = 20 Hz in Fig. 12 and f = 50 Hz in Fig. 13.

The sensor type depicted in Fig. 3 was used for the experiments. In all experiments, the influence of the surface defect on the magnetic parameters of the probes was significant. The influence is maximal at the spot where the center of the sensors induction coil is positioned mid above the surface defect (Position p = 5 cm distance to outer edge of the sensor). The parameters permeability, maximum induction and remanence show a minimum, the coercive force an inflexion point (Position p = 5 cm). Due to the smaller skin depth (penetration depth
of AC) at higher frequencies, at \( f = 50 \) Hz the minimum is considerably lower, so surface defects are easier to detect.

Fig. 13 and 14 show the percental changes of the magnetic parameters of two wires, the wire in Fig. 13 had two surface defects at a distance of 8 cm, the wire in Fig. 14 at a distance of 12 cm. Both defects are indicated by the maxima of the magnetic parameters. Further experiments showed, that even defects as small as 0.5 mm length or depth can be identified.

\[ \text{Figure 14. Magnetic parameters of a wire with two surface defects} \]

\[ \text{Figure 15. Magnetic parameters of a wire with two surface defects} \]

6 Conclusions

In this project a new and advanced measurement device, using magnetoelastic coil sensors, was developed. It allows to determine static or dynamic load changes in tendons and steel on up to 24 channels. Magnetoelastic coil sensors are suitable for the measurement of stress in prestressed steel in the course of the erection and life time of structures and members. Accordingly, they can be used for the determination of steel stress in suspension bridges and anchor systems. Unlike strain gauges the ME-sensors are also applicable on strands. The robust sensors are easy to mount and cannot be damaged by overloading. They are also mountable on almost every position along the tendon/steel rope, no changes in the building construction are necessary.

If free access to the tendon is provided, coil sensors are also suitable to detect surface defects and corrosion. The sensor has to be pulled along the tendon for inspection. Defects down to 0.5 mm can be found.

Acknowledgements

The financial support for the research program within the framework of the collaborative research center SFB 477 by the German Research Council DFG is gratefully acknowledged.

References