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# Magnetoelastische Kraftmessung im Spannbeton

## Magnetoelastic Force Measurement in Prestressed Concrete

## Mesure magnéto-élastique de la force dans le béton précontraint

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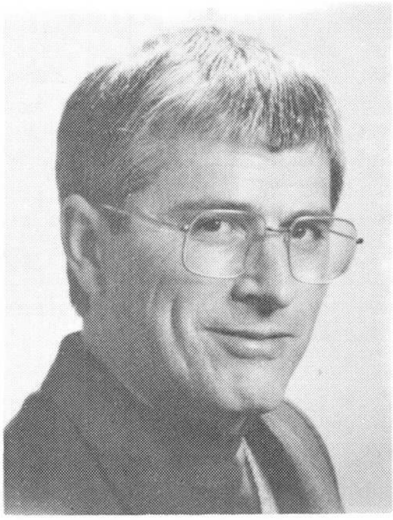

Beat Gimmel, geboren 1940, erwarb 1964 sein Diplom als Elektroingenieur an der ETH-Zürich. 1983 erhielt er am gleichen Ort den Titel Dr. sc. techn. Seit dieser Zeit arbeitet er fachübergreifend an der Abteilung für Massivbau an der EMPA in Dübendorf.

## ZUSAMMENFASSUNG

Die magnetischen, magnetoelastischen und andere damit im Zusammenhang stehenden physikalischen Eigenschaften von Spannstahl als Grundlage für die magnetoelastische Kraftmessung in den Spanngliedern von Spannbeton werden behandelt. Ein neuartiges empirisches Gesetz, welches die Modellierung der magnetoelastischen Messdaten gestattet, wird angegeben.

## SUMMARY

This paper discusses the magnetic, magnetoelastic properties and other related properties of prestressing steel as a basis for magnetoelastic force measurement in the tendons of reinforced concrete. A novel empirical relationship for interpreting the magnetoelastic measurement data is presented.

## RÉSUMÉ

Cet exposé traite des propriétés magnétiques, magnéto-élastiques et autres propriétés physiques liées aux aciers de précontrainte qui servent de base à la mesure magnéto-élastique de la force dans les câbles tendus dans le béton précontraint. Une nouvelle loi empirique permettant une modélisation des valeurs de mesures magnéto-élastiques est présentée.

## 1. INTRODUCTION

Since World War II, the number of architectural applications of prestressed concrete has been increasing continually. Today, countless structures throughout the world have been erected using this technology. Unfortunately, these structures are not always free of errors in design and execution. Combined with today's severe environmental conditions, this has led to increased evidence of damage. More than ever, the task of investigating exact damage causes within the framework of required maintenance work is of topical interest.

Although prestressed concrete behaves basically the same as untensioned reinforced concrete concerning the damage mechanism, the damage becomes especially significant in this type of construction in relation to the tendons, resp. the tensile force in them. Thus, knowledge of this tensile force is extremely important, above all where the condition of the structure is regarded as especially critical. Unfortuantely, at present there is hardly any possibility of determining the force occurring in a tendon of a prestressed concrete structure without entirely or partly destroying the tendon, unless special measures had been undertaken when the structure was erected. Methods to permit such a measurement without weakening the tendon were therefore explored.

One possibility is the magnetoelastic force measurement. The basic principles of this method and early experience with it are reported here.

## 2. FUNDAMENTALS

The magnetoelastic effect is based on the principle that the magnetic properties of a ferromagnetic wire change under the influence of a tensile or compressive force. The (J,H) curve which describes the magnetic behavior of a ferromagnetic material is deformed under application of a tensile force (see Fig.1).

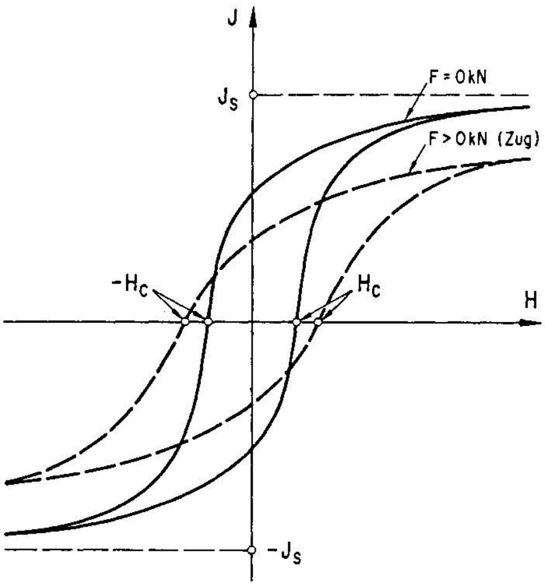


Fig.1 Magnetoelastic effect on prestressing steel

This magnetomechanical effect was discovered by E. Villari [Vil], who published his magnetoelastic observations in the middle of the last century. Closely related with the magnetoelastic effect is magnetostriction, discovered and published approx. 20 years before Villary by J.P.Joule. In this effect, the length of a ferromagnetic wire is changed by magnetizing it with a current-carrying coil. If the wire becomes longer, the effect is described as positive magnetostriction; otherwise as negative. Magnetostriction is also sometimes referred to as the JOULE effect. In everyday life, the effect can be observed in the buzzing of electrical transformers. Likewise, the magnetoelastic effect is known as VILLARI-effect.

Since changes of force and length on the same specimen are related through HOOK's law, the two effects can be regarded as inverse to one other. The idea to use the magnetoelastic effect for the force measurement originated with the originally Swedish firm ASEA (now ABB). The magnetoelastic stress gauge, designated as PRESSDUCTOR [Dah] proved to be very robust and suitable for severe industrial applications, such as the measurement of crane loads. Based on this idea the Belgian firm BEKAERT-COCKERILL attempted to construct an instrument for measuring the tensile force in the tendons of prestressed concrete. However, the force measurement was not based upon the principle of the stress gauge. Instead, it was attempted to utilize the prestressing steel itself as the measurement probe.

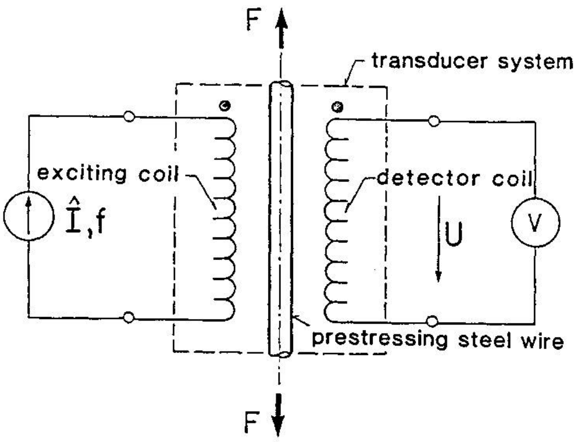


Fig.2 Magnetoelastic F-measurement

The technique of using stress gauges has the disadvantage that a measurement can be carried out only on the ends of the tendon, that is at the anchorages. This limitation can be avoided when stress gauges are not employed. Instead of the stress gauges, a measurement coil system is employed. This can be installed at any given position along the tendon. Offsetting this major advantage is the disadvantage that the force measurement is dependent upon the chemical composition and grain structure of the tendon. Since prestressing steel is a closely controlled material in regard to its mechanical strength (1500-1800 N/mm$^2$), its chemical composition lies within close tolerances.

## 3. THE MAGNETOELASTIC MEASUREMENT TECHNIQUE

The technique developed by the firm BEKAERT with the help of the Université Catholique de Louvain [Hal] is based on the following principle:

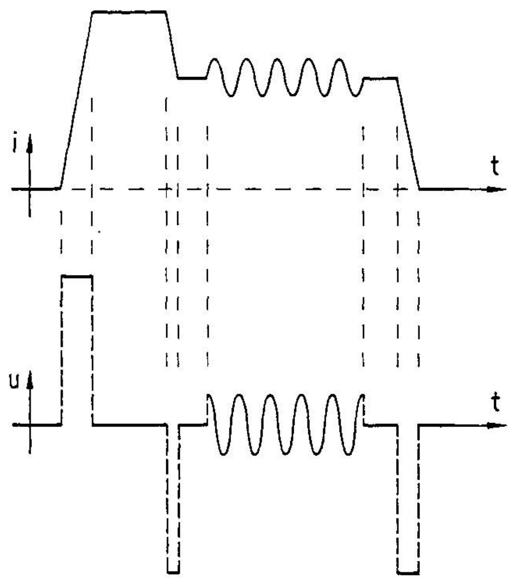


Fig.3 Excitation- and detectionsignal

An alternating current measurement impulse with a superposed alternating current burst as shown in Fig. 3 is applied to the exciting coil (see Fig. 2). The finite flanks of the measurement pulse limit the amplitude of the induced disturbing impulses in the detector winding. The current impulse at the onset drives the magnetization of the prestressing steel into saturation. This creates a defined working point on the (J,H) curve and serves to improve the repeatability of the measurement. The amplitude is then reduced to a second lower level. The actual measurement begins with the onset of the superimposed sinusoidal oscillation. This sinusoidal current induces a sinusoidal measurement voltage in the detector winding. This is measured with an RMS-voltmeter. The amplitude of the AC voltage at the output of the detector winding will be smaller of larger as a function of the magnitude of the mechanical tensile force in the prestressing steel.

The calibration curves of the firm BEKAERT were successfully repeated by the

Section Measurement Techniques of the EMPA and their linearity was confirmed. Nevertheless the following difficulties arose:

1. Since the measurement frequency of the currrent impulse is lower than 50 Hz, the low-pass filter of the RMS-voltmeter has an influence on the measurement result. However, this influence can be evaluated and compensated numerically.

2. By repeated measurement on the same specimen, the prestressing steel becomes warm due to eddy currents. Furthermore, the exiting coil heats up strongly due to copper losses.

3. In the flanks of the measurement impulse, large voltage peaks occur in the detection winding.

4. A visual inspection indicated that the quality of the electronic circuitry was deficient.

These observations led to an internal development at the EMPA within the framework of a research and development project to improve bridge maintenance.

## 4. MEASUREMENT OF THE ELCTRICAL, MAGNETIC AND MAGNETOELASTIC PROPERTIES OF PRESTRESSING STEEL

Since civil engineers are generally not interested in the electrical and magnetic properties of the material prestressing steel, technical data of this kind is not available. With respect to the electrical properties the electrical conductivity is of interest. This is significant in connection with eddy currents in the prestressing steel wire. To measure this quantity, three 7mm-diameter prestressing steel specimens from 3 different manufacturers were utilized (see Table 1). The ohmic resistances were determined with a Thomson bridge. The measurement of the (J,H) curves was carried out with a permeameter [IEC]. Thus, the magnetic data of three prestressing steel specimens were established for the unloaded condition (F = 0 kN). In order to be able to execute magnetoelastic measurements on wire specimens under tension, the construction of a tensioning frame was necessary. For the frame material,the nonmagnetic materials wood or unreinforced concrete were considered. Eventually wood was chosen, since it offers various advantages:

1. In dry condition, wood is an electrical insulator,
2. Wood is magnetically neutral,
3. Wood has a low specific density

and

4. Wood is naturally fiber-reinforced.

The wooden tensioning frame was dimensioned for a tensile force of 80 kN. The frame was designed to allow measurements with the permeameter as well as with measurement coils. With this frame, measurements were performed at various tensile stresses in 5 kN steps up to 30 kN. The same measurements, on the same prestressing steel specimens, were carried out as in the unloaded condition (F = 0 kN).

## 5. MEASUREMENT RESULTS

This section presents all of the data pertinent to the magnetoelastic force measurement, obtained on the three prestressing steel specimens from the three manufacturers.

### 5.1 Mechanical Properties

The 7 mm prestressing steel specimens from the three suppliers were coded with colors (see Table 1). The table also gives the mean strengths (determined from the mean values from the material specifications), as well as the minimum strength values, which are important for the dimensioning of structures. The mean diameter of the prestressing steel specimens is (7.00 ± .02)mm.

| Supplier: | Color code | Min. value $N/mm^2$ | Mean value $N/mm^2$ |
|---|---|---|---|
| VOGT | RED | 1670 | 1777±15 |
| BEKAERT | YELL | 1670 | 1757±17 |
| F + G | BLUE | 1670 | 1732±19 |

Table 1 Mechanical Strength Values of the Prestressing Steel Specimens

### 5.2 Chemical Composition

Since one of the prestressing steel specimen suppliers did not supply data on the chemical composition these measurements were performed in the EMPA Laboratories (Table 2). The majority of the EMPA values agreed with those of the suppliers within the measurement accuracy of the analysis instruments.

| Supplier: | | VOGT | BEK'RT | F + G |
|---|---|---|---|---|
| C | M.-% | .80 (.82) | .83 | .77 (.82) |
| Si | M.-% | .31 (.29) | .27 | .19 (.25) |
| Mn | M.-% | .61 (.55) | .65 | .62 (.57) |
| S | M.-% | .013 (.016) | .016 | .040 (.018) |
| P | M.-% | .013 (.017) | .026 | .003 (.008) |

Table 2 Chemical Composition of the Prestressing Steel Specimens, (.nn) = respective data from the supplier

### 5.3 Electric and magnetic Measurements

From the electrical measurement, only the resistance measurement are mentioned here, since they are significant for the eddy-current heating. The mean specific electrical resistance is calculated from the measurement data. It lies in the range (200 ± 20%)mOhm($mm^2$/m). The influence of the Si-content on the specific electrical resistance of electrical steels is known. The higher the Si-content, the higher is the specific electrical resistance of the prestressing steel.

The magnetic behavior of the prestressing steel can be described through four quantities, namely the initial permeability $\mu_{ar}$, the coercive field strength $H_c$, the residual induction $B_r$ and the saturation polarization $J_s$. The measurement data of these four magnetic quantities are given in Table 3.

| Supplier: | Color code | $\mu_{ar}$ | $H_c$ | $B_r$ | $J_s$ |
|---|---|---|---|---|---|
| | | 1 | A/cm | T | T |
| VOGT | RED | 57 | 13.2 | 1.26 | 2.03 |
| BEKAERT | YELL | 62 | 13.4 | 1.24 | 2.03 |
| F + G | BLUE | 63 | 12.4 | 1.22 | 2.06 |

Table 3 Magnetic Properties of Prestressing Steel

### 5.4 Magnetoelastic Measurements

In these measurements with the tensioning frame, another independent quantity the force comes into play. It appears reasonable to attempt to reduce the comprehensive measurement data. This is accomplished by modelling the (J,H) curve. Since the linearity of the magnetoelastic quantity $\mu_{\Delta r} = \mu_{\Delta r}(F)$ improves with increasing field strength, it appears reasonable for F = 0 to assume a magnetization law for high field strength given by WEISS [Boz.,p.484]

$$\frac{J}{J_s} = \left( 1 - \frac{\alpha H_o}{H} \right).$$

With the measurement data of the (J,H)-magnetization curve for F=0, the $J_s$ and $\alpha H_o$ values can be determined. This law can now be extended:

$$\frac{J}{J_s} = \left( 1 - \frac{\alpha H_o}{H} \left(1 + \frac{F}{\beta F_o}\right) \right),$$

so that the magnetoelastic behavior can be described quantitatively. In an analogous fashion, the parameter $\beta F_o$ can be determined with the help of the data for F>0.

For the specimen VOGT(RED) the following values are obtained:

$$a = \alpha H_o = 19.9 \text{ A/cm} \quad \text{und} \quad b = \beta F_o = 40.1 \text{ kN}.$$

Using these values, a very good agreement between measurement and model was achieved for the higher field strengths.

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