# QUANTITATIVE ASPECTS OF THE DETECTION OF RUPTURES OF PRE-STRESSED STEELS IN CONCRETE BEAMS USING THE MAGNETIC FLUX LEAKAGE MEASUREMENT METHOD

# QUANTITATIVE ASPEKTE DER DETEKTION VON SPANNSTAHLBRÜCHEN IN VORGESPANNTEN DECKENTRÄGERN MITTELS DER MAGNETISCHEN STREU-FELDMESSUNG

# ASPECTS QUANTITATIFS DE LA DETECTION DE RUPTURES D'ACIERS PRECONTRAINTS DANS DES POUTRES EN BETON SELON LA METHODE DE MESURE DE FLUX MAGNETIQUES

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## Summary

This paper represents results of theoretical investigations concerning the detection of ruptures of prestressed steels using the magnetic flux measurement method. Based on numerical calculations with regard to the nonlinear ferromagnetical behavior of steel the influence of some factors like distance probe/steel, crack width on the leakage field amplitudes has been investigated. As result of this investigations follows, that the usual dipole model is not sufficient for explaining the shape and amount of the magnetic leakage field. Due to the spatial distribution of the magnetization in the crack area, the leakage field amplitudes are relatated in a nonlinear manner to the crack width and decrease more weakly as in case of pure magnetic dipoles.



## Zusammenfassung

In diesem Artikel werden die Ergebnisse theoretischer Untersuchungen zur magnetischen Streuflußmessung von Spannstahlbrüchen dargestellt. Mittels numerischer Streufeldberechnungen wird der Einfluß einiger Faktoren wie Rißbreite, Abstand Sonde/Stahl auf die Streufeldmessung untersucht. Demnach kann der tatsächliche Streufeldverlauf im Bereich von Rissen nicht durch Annahme eines magnetischen Dipols befriedigend erklärt werden. Infolge einer räumlichen Verteilung der Magnetisierung im Bereich des Bruches hängt die Streufeldamplitude in nichtlinearer Weise von der Rißöffnung ab und nimmt ferner wesentlich schwächer ab, als nach dem Dipol-Modell zu erwarten wäre.

**Résumé**

Le rapport représente les résultats d'investigations théoriques sur la détection de ruptures d'aciers précontraints à l' aide de la méthode de mesure de flux magnétiques. Basé sur des calculs numériques en tenant compte du comportement ferromagnétique de l'acier l'influence de quelques facteurs comme la largeur de fissure, la distance sonde/acier sur la mesure du champ magnétique de dispersion est investigé. Selon cela le champ de dispersion effectif dans le domaine de fissuers ne peut pas être suffisamment expliqué par l'adoption d'un dipole magnétique. Par suite d'une répartitian spatiale de la magnétisation dans le domaine des fissures l'amplitude de champ de dispersion dépend d'une maniére nonlinéaire de l'ouverture de la fissure et diminue beaucoup moins fort que le modéle dipole laisse attendre.

**Keywords:** nondestructive evaluation,prestressed ceiling beams,magnetic flux leakage measurement,

## 1. Introduction

Recently the method of magnetic leakage flux measurement has come to be used for detection of wire ruptures in prestressed ceiling beams/1-3/. This method, which has been known for some time in civil engineering /4/, is based upon measuring the magnetic leakage flux both during or after exposure of the beams to a exterior magnetic field parallel to the wires. Ruptures in the prestressed steels produces typical anomalies in leakage field patterns. In practice, this method of investigation is used without the theoretical bases having been sufficiently clarified. According to /1,2/ the (remanent) leakage field results from the formation of a magnetic dipole on opposite sides of the crack. In reality, the pattern and especially the leakage field amplitudes do not match calculations which take into account the dipole-model (see Chapter 3). The actually registered field amplitudes lie considerably above the values expected from the dipole model. Likewise in the case of a valid dipole model there should be a strong proportional relation between crack width and leakage-field amplitudes. This would have considerable consequences in view of the possibility of detecting ruptures with small crack widths, since the field intensity for dipoles decreases with the cube power of the distance.
This result shows that the interpretation of measured field curves along the lines of the dipole model only leads to unrealistic results (e.g. crack widths are overestimated).
Further the reliable application of the leakage field method presupposes that the influence of such factors as crack width, wire diameter, probe/steel distance can be at least approximately calculated.
It is the aim of this paper to provide a theoretical evaluation of the influence of theese above factors as well as of possible magnetic shielding on the leakage field. Then based on theese results,the limits of use of the magnetic method will be discussed.

## 2. Theoretical Considerations

The magnetic leakage field measurement method as represented in /1-4/ is based upon magnetostatics. The foundations will be briefly described below (see. also /5-7/).

The magnetic status is given by the two field magnitudes $\underline{H}$ and $\underline{B}$, where $\underline{H}$ is the magnetic excitation (A/cm) or magnetic field intensity. The field magnitude $\underline{B}$ is designated as the magnetic induction (Vs/m²) or flux density. In a ponderable material the following relation exists between the two field magnitudes:

$$\underline{B} = \mu_o \cdot [\underline{H} + \underline{M}] \tag{1}$$

In equation (1) $\underline{M}$ constitutes the contribution of the material in the field intensity. If the magnetization depends upon $\underline{H}$, $\underline{B}$ results as:

$$\underline{B} = \mu \cdot \mu_o \cdot \underline{H} \tag{2a}$$

or

$$\underline{M} = (\mu - 1) \cdot \underline{H} \tag{2b}$$

where $\mu_o$ is the permeability of the vacuum. In the following equations this is not explicitly taken into consideration. That means $\mu_o$ is made identical with 1. The two equations (2a,b) constitute a magnetic material law, where the relative permeability $\mu$ is considered to be a material property. In the case of ferromagnetic materials permeability is influenced in a nonlinear manner by the field intensity $\underline{H}$ (see Fig.1).

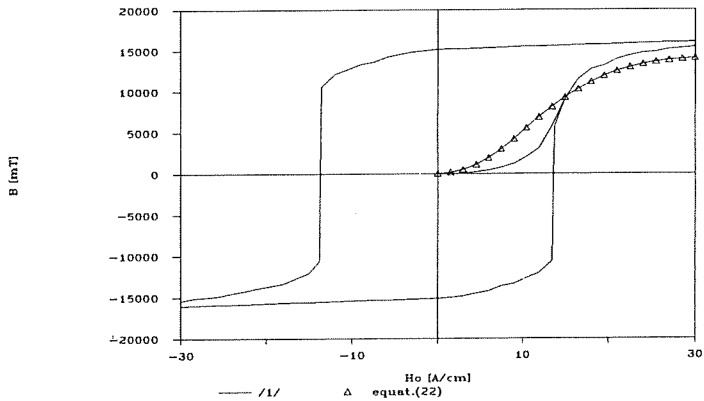



Fig.1 Magnetical Behavior of a prestressed steel [/1/]

It is useful to formulate the material law (2) incrementally:

$$\Delta \underline{B} = \mu_d \cdot \Delta \underline{H} \tag{3a}$$

In this case $\mu_d$ is the differential permeability, which still depends upon the field-intensity $\underline{H}$. In the case of isotropic material $\mu_d$ is a function of the amount of $\underline{H}$:

$$\mu_d = \mu_d; \qquad H = (\underline{H}^T \cdot \underline{H})^{1/2} \tag{3b}$$

Taking into account the remanent behaviour of material (hysteresis) $\mu_d$ depends upon the change in the amount of $\underline{H}$.

$$\mu_d = \begin{cases} \mu_d : & \Delta \underline{H}^T \cdot \underline{H} \geq 0 \\ \mu_{d-} : & \Delta \underline{H}^T \cdot \underline{H} < 0 \end{cases} \tag{3c}$$

In order to simplify matters, in this paper the differential permeability $\mu_{d-}$ will be fixed at 1, the magnetization stays even after the exterior field has been switched off.

The relations (4,5) follows from the Maxwell equations:

$$\text{div}\ \underline{B} = \delta B_x/\delta x + \delta B_y/\delta y + \delta B_z/\delta z = 0 \tag{4}$$

$$\text{rot}\ \underline{H}=(\delta H_y/\delta x-\delta H_x/\delta y)\underline{e}_z+(\delta H_x/\delta z-\delta H_z/\delta x)\underline{e}_y+ +(\delta H_z/\delta x-\delta H_x/\delta z)\underline{e}_x = \underline{j} \tag{5}$$

Equat.(5) describes the absence of sources of the magnetic induction (the magnetic lines of forces are always closed), whereas equat.(4) describes the circulation law, where $\underline{j}$ constitutes the electric current density. $\underline{e}_i$ are unitary vectors for the three spatial directions x,y z.

We consider the case that an element in which the relative permeability $\mu$ locally varies (for instance due to cracks or flaws) is exposed to a magnetic field $\underline{H}_o$. Electrical currents are excluded in the volume considered ($\underline{j}$=0). The resulting magnetic field intensity $\underline{H}$ is considered as superposing the excitatory field $\underline{H}_o$ and the leakage field $\underline{H}_s$.

$$\underline{H} = \underline{H}_o + \underline{H}_s \tag{6a}$$

Because rot $\underline{H}_s$ = 0, the leakage field can be obtained by means of a scalar potential $\phi$ :

$$\underline{H}_s = -\text{grad}\ \phi \tag{6b}$$

If (6b) is incorporated into (4) the following relation obtains for $\phi$:

$$\text{div grad}\ \phi = \text{div}\ \underline{M} \tag{7}$$

When determining the magnetic potential $\phi$, a differentation has to be made between whether the magnetization $\underline{M}$ may be assumed as known or it must be considered as a function of $\underline{H}$. In the first case (calculation of the field of a permanent magnet) the determination of $\phi$ may be regarded as summation equation. From (7) we obtain the well-known solution formula /5/:

$$-4\pi\cdot\phi = \int \text{div } \underline{M}\cdot 1/R\cdot dV + \int M_n\cdot 1/R\cdot dS \qquad (8)$$

Here R is the distance between the source point and the integrationspoint, while $M_n$ is the magnetization perpendicular to the surface S. If the magnetization in a volume element depends on $\underline{H}$, the material law (2a) has to be taken into consideration. The potential $\phi$ is specified by the following equation:

$$\text{div}(\mu.\text{grad } \phi) = \mu\cdot\text{div}\underline{H}_o + (\text{grad } \mu)_T\cdot\underline{H}_o \qquad (9)$$

In the case of a homogeneous field $\underline{H}_o$, spatial changes in the relative permeability produce the leakage field. At a sufficient distance from the area of investigation the leakage field disappears:

$$\phi(R\to\infty)=0 \qquad (10)$$

If permeability jumps occur across S, the boundary conditions (11) follows from (5):

$$\mu_1\cdot(\underline{H}_{o1}+\underline{H}_{s1})^T\cdot\underline{e}_n = \mu_2\cdot(\underline{H}_{o1}+\underline{H}_{s2})^T\cdot\underline{e}_n \qquad (11a)$$

$$\phi_1 = \phi_2 \qquad (11b)$$

The normal components of the magnetic induction and the magnetic potential run steady on the surface.

In the special case of an ellipsoid-shaped body featuring a constant relative permeability in a homogeneous field parallel to an axis the analytic solution is wellknown /5/. A constant field $\underline{H}_i$ is set up in the interior of the body. By means of the "demagnetisations-number" N , which is dependent only on the geometry of the body, the inner field is obtained as:

$$H_i = H_o/(1+(\mu-1)\cdot N) \qquad (12)$$

A general solution of the equat.(7) is not known, so that approximation methods have to be used. Methods based upon minimizing a energy functional prove to be especially effective in view of the numerical calculations /6,8,9/. The divergence-relation (6,8) is represented as an Euler-Lagrange-equation. For that purpose we consider the functional E:

$$E = \int_V \int_0^{\underline{H}} \underline{B}^T \cdot d\underline{H}' \cdot dV \qquad (13)$$

Furthermore equat. (14a) holds

$$\phi = \phi_o + t\cdot\delta\phi \qquad (14a)$$

where $\delta\phi$ is a freely chosen variation of the potential $\phi$. The first differential quotient from E to t at t=0 taking into consideration the boundary condition (10) is :

$$dE/dt = \int_V -(\mathrm{grad}\,\delta\phi)^T \cdot \underline{B} \cdot dV \cdot dV = \int_V \delta\phi \cdot \mathrm{div}(\underline{H}_o - \mathrm{grad}\,\phi_o + \underline{M}) \cdot dV \tag{14b}$$

The second derivation for t yields:

$$d^2E/dt^2 = \int (\mathrm{grad}\,\delta\phi)^T \cdot (\mathrm{grad}\,\delta\phi) \cdot (1+\mu) \cdot dV \tag{14c}$$

If (14b) in independence of $\delta\phi$ disappears, the divergence equat. (7) or (8) is fullfilled. If one assumes that $\mu$ is always positive, (14c) is always bigger or else equals zero. The functional E assumes a minimum valve. If an approximation formula for $\phi$ is introduced into (12) as:

$$\phi = \phi_k \cdot f_k(x,y,z) \quad ; \quad k=1,..n \tag{14d}$$

where $f_i$ are interpolation functions, the unknown coefficients $\phi_i$ can be determined from

$$\delta E/\delta\phi_k = 0 \tag{15}$$

In this case, the application of the method of finite elements is important for approximative determination of the leakage field potential. In order to allow the consideration of non-linear permeability, equat. (4) or (13) is solved in an incremental way. For this purpose, it is assumed that the exterior field $\underline{H}_o$ is "applied" in incremental steps $\blacktriangle\underline{H}^i$. We further assume that in an i-th iteration step $\underline{B}^i$ satisfies the divergence relation. The increment $\blacktriangle\underline{B}^i$ must equally satisfy equat. (4). If the increments are very small, the increment material-law (3) may be used. We assume that $\underline{B}^i(\underline{H}_o)$ already satisfies the divergence relation (4). In the case of a small change in $\blacktriangle H_o$ the functional to be minimized obtains as follows :

$$\Delta E = \int_V \int_{\underline{0}}^{\Delta \underline{H}^i - \mathrm{grad}(\Delta\phi)} \mu_d \cdot \Delta \underline{H}' \cdot d(\Delta \underline{H}') \cdot dV$$

After integration over $\Delta \underline{H}$ the volume integral to be minimized is:

$$\Delta E = \int \tfrac{1}{2} \cdot \mu_d(H^i) \cdot (\Delta \underline{H}^i_o - \mathrm{grad}\Delta\phi)^T \cdot (\Delta \underline{H}^i_o - \mathrm{grad}\Delta\phi) \cdot dV \qquad (16)$$

Using the interpolation equations (14d), the coefficients $\Delta\Phi_1$ in line with (15) are determined as follows:

$$\Delta \underline{\Phi}^i = \underline{K}^{-1} \cdot \Delta g_i \qquad (17)$$

yielding:

$$\Delta \phi^{iT} = [\Delta \phi^i_1, \ldots, \Delta \phi^i_n]$$

$$\Delta \underline{g}^{iT} = [\Delta g^i_1, \ldots, \Delta g^i_n]$$

$$\Delta g^i_{k1} = \int_V \mu_d(H_i) \cdot (\mathrm{grad}\ f_k)^T \cdot \Delta \underline{H}^i_o \cdot dV$$

The magnetic potential of the leakage field after the i-th iteration step (increment) now becomes:

$$\underline{\Phi}^T = [\sum_0^i \Delta \phi^j_1, \ldots, \sum_0^i \Delta \phi^j_n -] \qquad (18)$$

This equation (17) provides a vectorial formulation of the magneto-static boundary value problem and is, in this form, especially appropriate for performing numerical calculations with the finite element method(FEM). On the basis of small increases to the exterior field $\blacktriangle \underline{H}_0$ the differential permeability can always be determined from the field of the preceding iteration section, thanks to which the calculation of the "permeability matrix" $\underline{K}$ is very simple in each iteration step.

### 3. Application of the calculation model

**Geometrical Idealisation of prestressed steel ruptures**

For simplicity's sake, a ruptured prestressed steel can be represented by the axial-symmetric idealization shown in Fig. 3. The essential parameters are : $d_s$-diameter of steel, w- crackwidth, $l_w$ -crack distance, $l_1$-scope of laeakage field

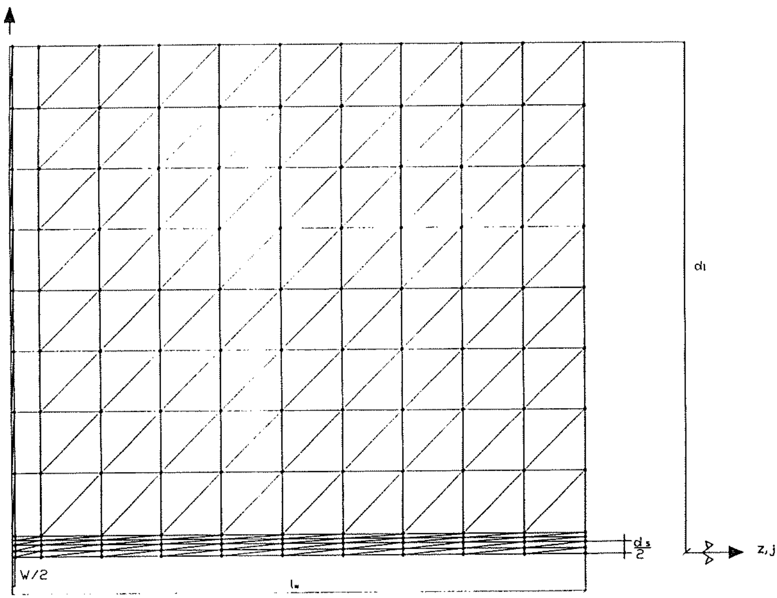



Fig.2 Finite element idealization of ruptures

In view of the "radial scope" of the leakage field, it is supposed that this has completely disappeared by a distance $d_1$ from the system axis. The boundary conditions of the magnetic potential $\Phi$ are:

symmetry of the magnetic field:

$$\Phi(r,z) = -\phi(r,-z) \qquad (19\ a,b)$$

$$\phi(r,0) = 0$$

"scope" of the leakage field:

$$\Phi\ (d_1,z) = 0 \qquad (19\ c)$$

The exterior field is supposed to be homogeneous to the axis of steel. Hence:

$$\underline{H}_o^T = [0,H_o]$$

**3.1 Dipole Approximation:**

As the most simple solution, we consider the dipole approximation assuming $l_w = \infty$ . As shown in Fig.1 we start from a homogeneous saturation magnetization $M_s \approx 15000$ A/cm. In this case the vector of magnetization $\underline{M}$ is:

$$\underline{M}^T = [0,15000] \ ; \qquad 0 \le r \le d_s/2 \ , \ |z| \ge w/2$$

The tangential component of the leakage field $H_{sz}$ may be calculated using the equation (7), here attention has to be paid to the magnetization of the crack surfaces and the spatial divergence is set at zero. The dipole approximation results in:

$$H_{sz} = 1/16 \cdot w \cdot M_s \cdot d_s^2/R^3 \cdot (1 - 3 \cdot z^2/R^2) \qquad (20)$$

According to this formula, the leakage field is directly proportional to the crack width w and the magnetization. The distance factor of the maximum amplitude in relation to the crack at z = 0 decreases with the cube of the distance R of the probe from the crack.

Fig. 3 plots the course of the tangential component of the leakage field $H_{sz}$ at a distance r = 45 mm from the middle axis (40 mm from the steel surface) calculated according to equat. (20).

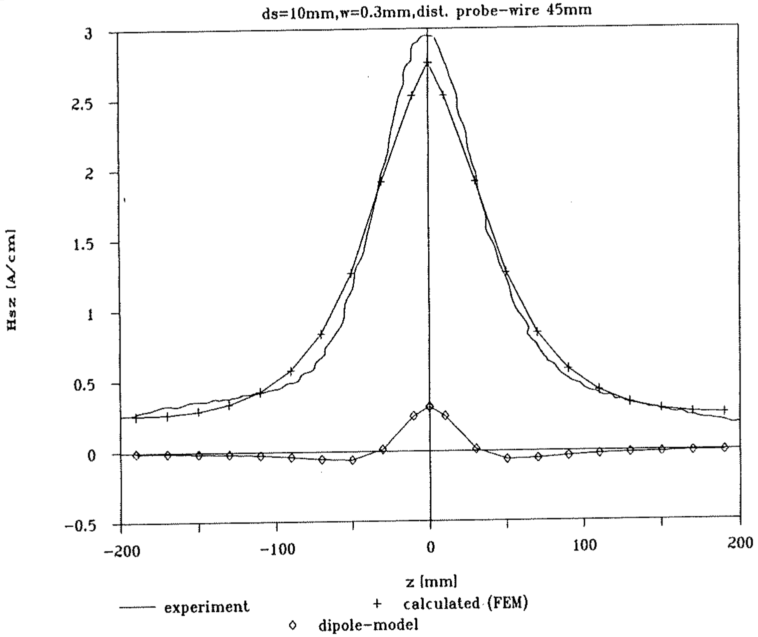



Fig.3 Comparison betw. experiment and calculation (w=0.15mm, $d_s$=10 mm, $H_o$=20A/cm, dist. probe/steel 45mm), $M_z$=15000 A/cm

For comparative purposes Fig. 3 represents the measured leakage-field with the same distance parameters, crack width etc. The field intensity of the excitatory field was about 20 A/cm. Fig. 3 shows that in a dipole approximation the real leakage field intensities may not be reached at all. Furthermore, the test shows an essentially smoother progression for the leakage field. The dipole model is not sufficient to explain the real leakage field. The assumption of a homogeneous magnetization of the steels with the crack borders being characterized by dipoles is therefore too a big simplification. In more exact calculations, an inhomogeneous magnetization taking into consideration the nonlinear material relation (3) becomes necessary.

### 3.2 Results of the finite element calculations

By drawing on to the finite element idealization represented in Fig. 2 and taking into account the assumptions made in chapter 3.1 an approximative computation of the magnetic potential $\Phi$ could be realized. For this purpose, triangular elements were used to determine the leakage potential of the points of intersection.

The leakage field at the points of intersection (i,j) was determined as follows:

$$H_{sz}(i,j) = -\tfrac{1}{2}\left[\frac{\phi(i,j)-\phi(i,j-1)}{z(j)-z(j-1)} + \frac{\phi(i,j+1)-\phi(i,j)}{z(j+1)-z(j)}\right]$$

$$H_{sr}(i,j) = -\tfrac{1}{2}\left[\frac{\phi(i,j)-\phi(i-1,j)}{r(j)-r(i-1)} + \frac{\phi(i+1,j)-\phi(i,j)}{r(i+1)-r(i)}\right] \qquad (21)$$

In order to determine the relative permeability in relation to the field intensity H an ad hoc equation was used:

$$\mu_d = [\mu_{oo}+\mu_1 \cdot H^{2.2}] \cdot \exp(-\mu_3 \cdot H^{1.5}) + 1 \qquad (22)$$

with $\mu_{oo}$= 80; $\mu_1$=17 [(A/cm)$^{-2.2}$]; $\mu_3$=0.037 [(A/cm)$_{-1.5}$], where H is the field intensity(amount) in the volume element considered.

In the calculations the leakage field was determined during application of a homogeneous field to the beam. For this purpose, a bar of diameter $d_B$ = 10 mm was considered, featuring cracks spaced at a distance of $l_w$ = 400 mm at several crack widths. The "scope" $d_1$ of the leakage field was assumed to be 167 mm. The exterior field $H_o$ was increased from 0 to 40 A/cm in steps of 2 A/cm. In Fig. 5 a,b some calculated leakage fields were shown.

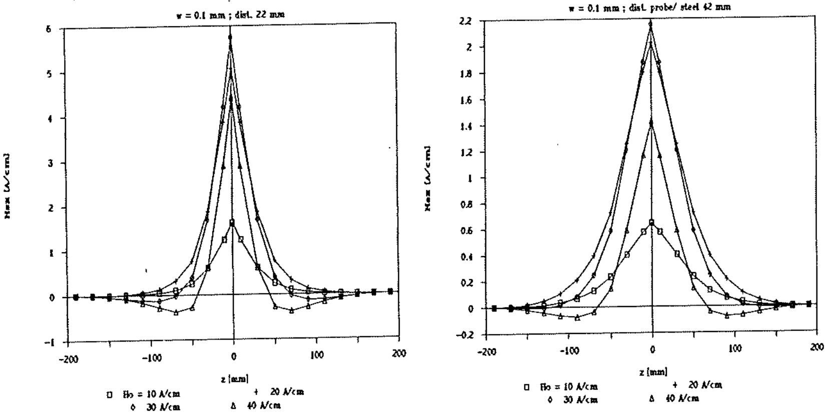
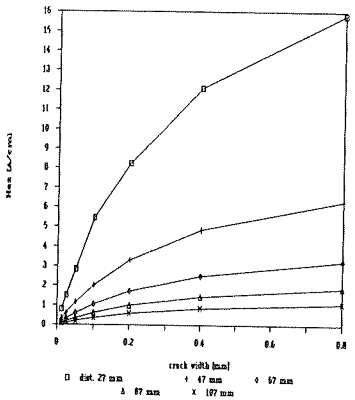



Fig.4a,b leakage field intensity ($H_{sz}$) w=0.0125mm
dist./probe 22,42 mm

It is at once apparent, at least with a view to extent and quality that there is a good accord between theory and experiment (Fig. 3). However, it has to be taken into consideration, that in the experiments the magnetization is provided by a yoke magnet, which is moved along the prestressed steel; the calculations however, assume a homogeneous exterior field which is oriented along the prestressing steels. The real lack of homogeneity of the exterior magnetic field was not taken into consideration in the calculations. That is why the calculated and measured results may not be completely compared.
The prestressed steel ruptures are represented by relatively broad graph of curves. The highest amplitude is reached (at z=0 i.e. above the crack) for an exterior field of about 30 A/cm. The "basis" of a crack signal extends over about 100 mm. When the exterior field intensity is increased to 40 A/cm, the leakage field amplitudes decrease considerably;

the signal rather resembles the dipole signal represented in Fig. 3a. This is due to the increase in the magnetic saturation of the steel in the course of which the magnetization becomes more homogeneous. With an increase in the exterior magnetic field intensity the leakage field is reduced again. In order to reach high leakage field amplitudes,the optimal field intensity of the excitatory field should be chosen. Numerical analysis demonstrates conclusively that for field intensities of 20 - 30 A/cm the magnetization on the bars is so inhomogeneous that small cracks with a width of 0.01 mm may be detected.

Furthermore, the influence of crack width w upon the leakage field intensity was investigated. On the whole crack widths were varied between 0.0125 mm and 0.8 mm. Based on the above considerations the excitatory field is set at 20 A/cm. Fig. 5a contains the leakage field amplitudes $H_{sz}$ at z = 0 in dependence on the crack width w. Further Fig. 5b contains the maximum leakage field amplitude $H_{sz}$ for the crack width w = 0,2 mm as a function of the distance of the measuring probe from the middle axis of the prestressed steel.



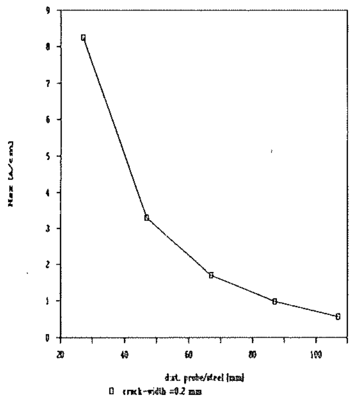




Fig.5a Maximal leakage field amplitude (A/cm)$H_{sz}$ at z=0, depending on crack width ,probe/steel dist. 22 mm)

Fig.5b Maximal leakage field amplitude (A/cm)$H_{sz}$at z=0 depending on probe-steel distance

It is evident that the maximum leakage field amplitude depends in a non-linear way on the crack width, whereas the influence of the crack width on the leakage field amplitude is not so big. However, when there is an unknown distance of the probe to the prestressed steel, it is not possible to determine exactly the crack width from the maximum leakage field amplitude.

With regard to the influence of the (radial) distance of the measurement probe to the prestressed steel surface, our calculations show that the leakage field amplitudes in the distance area about 20 -80 mm (which are of relevance to practical measurements) decrease proportionally to $1/r^{-2}$. The result is an essentially weaker decrease in the leakage field than would be expected according to the dipole approximation. The good chances of detecting ruptures with small crack widths even in cases of relatively big distance to the prestressed steel is due to this "harmless" distance behavior of the leakagefield as well as to the non-linear connection between the field amplitudes and the crack width. The physical reason for this is the inhomogeneous magnetization of the prestressed steels in the vicinity of the ruptures. The simple dipole model, according to which the crack borders of a prestressed steel ruptures have to be regarded as magnetic poles, is not sufficient for a quantitative explanation of the results of leakage field measurements.

### 3.3 Influence of shields and stirrups

While applying the leakage field method in practice, the conditions prevailing are generally more complicated than the assumptions described in 3.1-2. This refers especially to the fact that in most cases several prestressed steels are ranged side by side. Furthermore, besides the longitudinal prestressed bars, there are also transversal stirrups, wires, and slack reinforcements. Especially complicated is the case of prestressed bars in shields.

There are two reasons for difficulties to detect ruptures in prestressed steel bars. On the one hand, there is the additional structural elements (stirrups, wires etc.) produce leakage field signals which become superposed over the crack signals. On the other hand, additional ferromagnetic structural elements cause the magnetic leakage flux to be magnetically shielded. This is naturally the case with jackets. But even for prestressed bars that run parallel, a certain shielding effect may detected, i.e. the signal exhibited by a broken prestressed bar is weakened if the neighbouring prestressed bars have no cracks at the same place.

First of let us consider the influence of jackets. For this purpose we assume that the prestressed steel is surrounded by a jacket of ferro-magnetic material (see Fig.6).

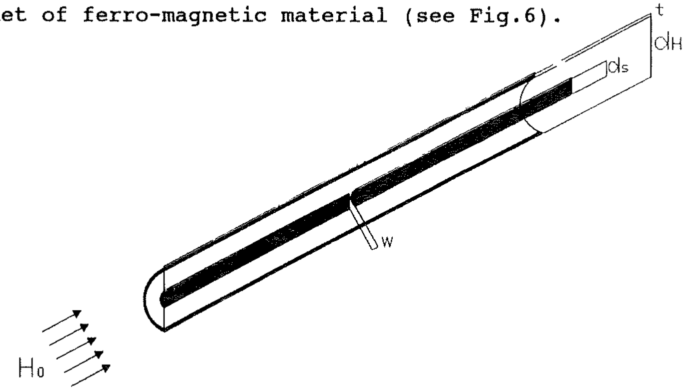



Fig. 6 Schematic representation of magnetic shielding of prestressed steel

In the most simple case, we also assume a homogeneous exterior field parallel to the jacket and the prestressed steel. In this case, the prestressed steel is also magnetized, but the field lines of the leakage flux must still "penetrate" the jacket before they reach the probe. We consider again a steel with $d_s$ = 10 mm, which has a rupture at z = 0 with w = 0.1 mm. This bar is assumed to be enveloped by a 1 mm thick jacket of the same ferromagnetic material. Further, the jakket diameter $d_h$ is assumed to be 6 mm and 30 mm, and the exterior magnetic field is assumed to be parallel to the longitudinal axis. Fig. 7 represents the calculated leakage field curves (tangential component) at different distances to the jacket

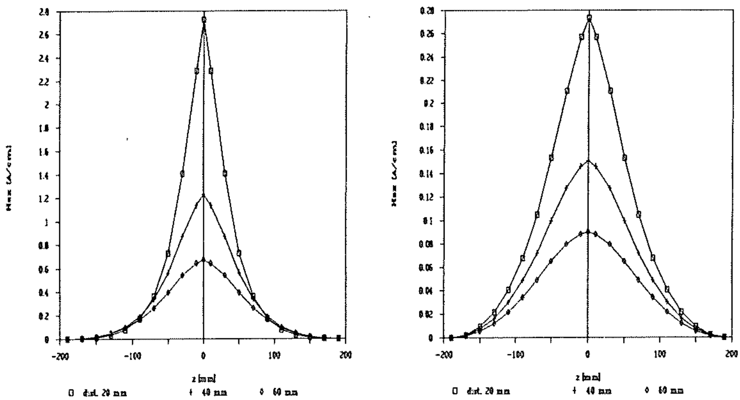
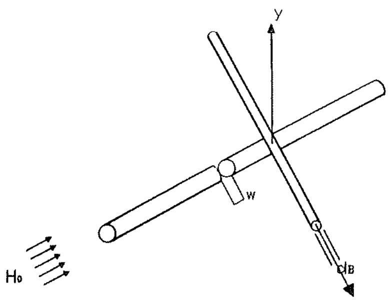



Fig.7a Leakage field intensity(A/cm), w=0.1mm , $d_s$=10 mm, inner diameter of jacket 12mm, thickness of jacket 1mm exterior field $H_o$=20 A/cm

Fig.7b Leakage field intensity(A/cm), w=0.1mm , $d_s$=10 mm, inner diameter of jacket 30mm, thickness of jacket 1mm exterior field $H_o$=20 A/cm

It is evident that the jacket has a shielding effect. In the case of closer shield (jacket diameter 12 mm) the leakage field amplitudes were reduced to about 50 % of the values existing without the jacket. For a wider shield (jacket diameter 30 mm) the field amplitudes were even reduced to 10 % of the original values. The shape of the leakage field becomes flatter than in case of missing shields, the cracks are therefore represented less clear. It may, however, happen

that for a wide shielding the crack signal may be improved by recourse to a more intense magnetic field $H_o$ (see Fig.8c). This is obviously due to the different degree of homogeneity of magnetization found in shielded and prestressed bars. Ideally the shielding should be quite homogeneous magnetized in the direction of the z-axis and naturally does not contribute to the leakage field which then is completely determined by the field of the wire. The shielding is thus "invisible" from magnetic a point of view.
In the following, we shall focus on the problem of the influence of transverse arranged stirrups. (see Fig. 8).



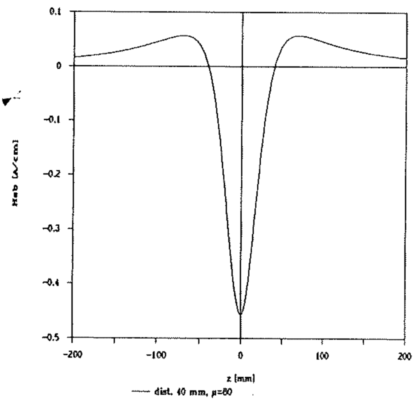



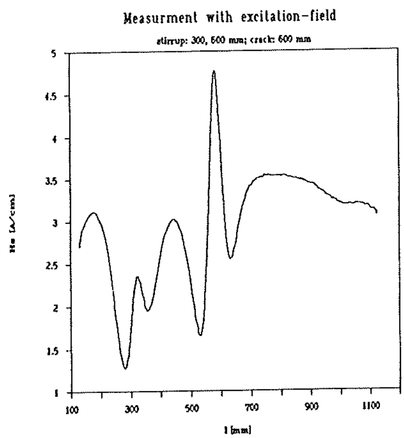

Fig.8a Schematic representation of stirrups

Fig.8b Leakage field (A/cm)of a transversely arranged stirrup calculated with equat. (23) $d_b$=10mm, $H_o$=30A/cm,probe/stirrup dist. 40mm

The calculation of the leakage field of such a arrangement has to take into account the complete three-dimensional geometry and is therefore very comprehensive. In order to realize a rough approximative determination of the influence of stirrups, those are considered as infinitely extended cylinders with a diameter $d_b$. The leakage field of cylinders in a homogenous exterior field may be calculated exactly. The result is with $\mu$ as effetive permeability (/7/) is as follows:

$$H_{bz} = H_o \cdot \frac{\mu-1}{\mu+1} \cdot \frac{d_b^2}{4 \cdot R^2} \cdot \left[\frac{z^2-y^2}{R^2}\right], \quad H_{br} = H_o \, \frac{\mu-1}{\mu+1} \cdot \frac{d_b^2}{R^{'}} \cdot \frac{z \cdot y}{2R^2} \qquad (23)$$

The leakage field exhibits qualitively a shape similar to a negative crack signal; stirrup signals may be distinguished from crack signals by a reversed sign (see Fig. 8b). Due to the demagnetization coefficient N=0.5 of the cylindrical body, the interior field in the stirrup is according to (12) lower than in the prestressing wire, which is positioned along the axis of the exterior field (N=0). Hence the remanent field of the stirrups is expected to be considerably smaller than the remaining field of the axially arranged wire. Thus the signals produced by the stirrups, which during



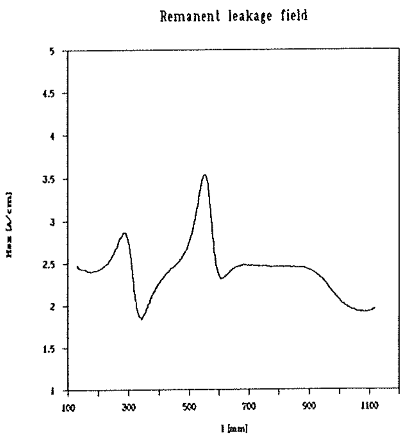




Fig.9a Measured leakage field(A/cm) with exterior field

Fig.9b Measurement of the remanent field measurement in the active field $\underline{H}_o$ are proportional to $H_o^2 d_b^2/R^2$, appear to be considerably reduced, when the residual field is measured (see Fig. 9).

Based upon the comparison of signals measured in the active and the remanent field, the signals which have very different patterns and amplitudes indicate stirrups, wires, etc. positioned transversly to the prestressed steel. But even measuring of the remanent field due to the suppression of stirrup signals permits ruptures of prestressed bars to be inferred with sufficient accuracy(see /1-3/).

**4.Conclusions**

In the present paper the leakage field of a cracked prestressed bar were calculated on the basis of the axial symmetry. The following conclusions may be drawn:

- The dipole model in which the crack borders as magnetic poles give rise to the leakage field is in insufficient for the interpretation of realistic field patterns.
- Taking into account ferromagnetic material behavior, the leakage field may be simulated by means of numerical procedures that accord satisfactorily with experiments
- The distance behavior (probe/steel) of the leakage field in the area relevant for practical measures does not vary in line with the dependency $1/R^3$ but instead decreases more weakly.
- Between the leakage field amplitude and the crack width there is a nonlinear relation. Based on our calculations, the detection of cracks with a width of w=0.01 mm seems feasible. However for an minuscule crack widths detection is impossible.
- Ferromagnetic material behavior assures that the leakage field amplitudes for higher intensities of the exterior field are reduced as a result of attainment

of magnetic saturation. The shape of the crack-signals approximates to the leakage field similarly to the dipole model.

As for the problem of crack detection, it must be stated that the detection limit is normally determined by the electronic noise of the equipment. Further, the distinguishability of the crack signals has limits placed on it by signals of other elements (an open wire end produces a similar signal to a real steel rupture). Thus the limit of crack detection are not at all specified by the geomagnetic field as assumed in /1/. The analysis based on realistic assumptions concerning crack widths shows, that even for distances between probe/prestressed steel of up to 60 mm the leakage field amplitudes are bigger than the geomagnetic field (≈0.4 A/cm).Based on the above analysis, the leakage field within a area of up to 5 A/cm may be measured with an accuracy of 0.05 A/cm. Such accuracy may be readily achieved using commercially available sensors. An essential improvement in crack detection may be envisioned using tomographic procedures for the evaluation of signals. In this case, the distribution of permeability in the investigated volume i(permeability-matrix $\underline{\mathbf{K}}$) would be determined on the basis of the measured leakage field. Any solution of this problem must explicitly consider the hysteresis behavior of ferromagnetic material and to this end the detection of prestressed steel ruptures in jackets offers a promising lead.

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