ET-NDE of the Thickness Reduction of A Reinforced Concrete Embedded Steel Cylinder Pipe

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Abstract. Many water pipes used in distribution networks (cooling system, fire network, drainage...) are constituted of a core welded sheet coated with reinforced concrete. Steel constitutive of these pipes, in particular when in contact with sea water, are subject to corrosion. This corrosion involves reduction of the metallic core sheet thickness, which could affect the watertightness and the mechanical resistance of the pipe. The knowledge of the residual thickness of this steel sheet is a good indicator of the damage state, remaining life time of this sheet and general watertightness. Therefore, a common feasibility study between the CEA and EDF was carried out in order to demonstrate the feasibility of a steel sheet thickness measurement using electromagnetic methods. The CIVA modelling software dedicated to Non Destructive Testing was used during this study to understand physics phenomena and to optimise the probe design. This study shows that the use of a low frequency electromagnetic field and a micro-Fluxgate (high sensitivity magnetometer developed by the CEA) allows to measure the thickness of the metallic core sheet covered by a layer of concrete (without reinforcement) with a thickness up to 30 mm. The study also showed that a discrimination between a low thickness sheet and a nominal sheet thickness of 2 mm is possible through a layer of concrete with a thickness up to 40 mm in spite of the steel reinforcement bars.

Introduction

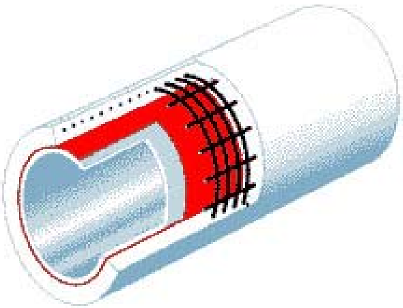
A method based on Eddy Currents and a sensitive magnetometer for Non Destructive Evaluation of a reinforced concrete embedded steel cylinder pipe was developed between CEA[1] and EDF[2].

Due to the porosity of concrete's layers, the steel (cylindrical sheet and reinforcement) of that kind of pipe is in contact with water and therefore is subject to corrosion. In order to maintain the circuit in operational conditions, a tool is required to detect the possible thickness reduction of the cylinder sheet.

This document exposes the feasibility study of this measurement method for the evaluation of the thickness reduction of the core steel sheet. Simulations with the Eddy Current module of CIVA [1] and experimental tests results are presented.

[1] Commissariat à l'Energie Atomique.
[2] Electricité De France.

Pipe structure



The considered pipe is constituted of a core welded steel sheet coated with reinforced concrete. This sheet is a steel band twisted and welded in a spiral.

The reinforcement structure is made of twelve longitudinal steel wires equally distributed along the perimeter and welded with a spiral steel wire.

The following table lists the geometrical parameters of the pipe.

Parameter	Nominal value (mm)
Steel sheet thickness	2
Reinforcement wire diameter	6
Space between turns of reinforcement	20
Space between longitudinal reinforcement	180
Total reinforcement thickness (2 wires)	12
Inner concrete thickness	22
Outer concrete thickness (typical lift-off)	36
Inner pipe diameter	600
Outer pipe diameter	730

Table 1: Parameters of the pipe

Simulation

A feasibility study based on simulation was made using simulation Eddy current module of CIVA in order to determine the appropriate measurement method for the evaluation of the core steel sheet thickness. CIVA was used to compute the influence on the magnetic induction of different parameters:

- core steel sheet thickness (e), varying with corrosion,
- the variation of the thickness of the layer of concrete (manufacturing process) which is referred also as "lift-off" (sensor – steel sheet distance: E),
- steel grade (relative permeability μ_r and conductivity σ),

The typical values of the relative permeability and conductivity of the steel sheet used for the simulation are:

$$\mu_r = 1000 \; ; \; \sigma = 6.10^6 \; S.m^{-1}$$

The amplitude of an electromagnetic plane wave arriving on a half infinite and homogenous space is exponentially attenuated as following:

$$A(z) = A_0 . e^{-\frac{z}{\delta}}$$ where δ is the standard penetration depth.

As in our case, the geometry is different and non infinite, this relationship is used as an approximated expression for the evaluation of the standard penetration depth. This quantity can be determined using the following relationship: $\delta = \dfrac{1}{\sqrt{\pi f \mu \sigma}}$.

where:

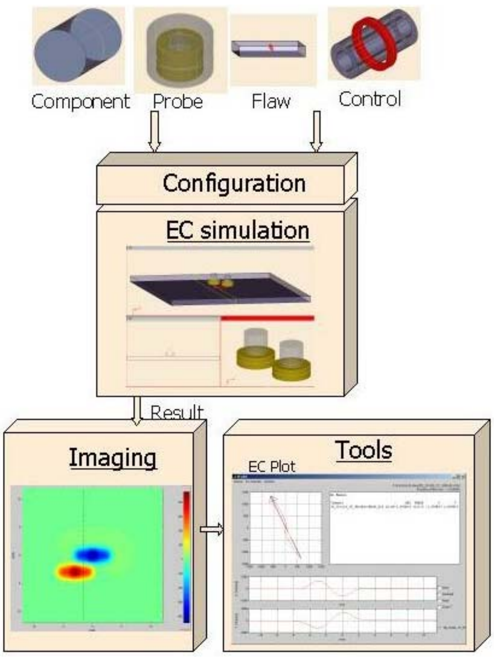
- f is the sensor excitation frequency,
- μ is the magnetic permeability,
- σ is the electric conductivity.

μ and σ values are given by the steel grade.

Therefore, the only variable to define δ is the frequency *f* which was set to 10 Hz. Thus the standard depth penetration was 2 mm.

The CIVA software was used to calculate the impedance variation for an absolute or differential sensor, the induced current density distribution, the electromagnetic fields and the potential vector. CIVA also provides a comparison between simulation and experimental tests.

The simulation of various probe arrangements lead to the design of an optimised probe which could differentiate steel sheet thickness signal from lift-off signal.



The sensing device is a micro-Fluxgate, a high sensitive magnetometer developed by the CEA/LETI which allows local magnetic induction measurement. The driving coil and the micro-Fluxgate sensor will be called "Fluxgate" in following text.

The signals corresponding to the vertical magnetic induction (B_Z), sensed by the micro-Fluxgate, are displayed in the complex plane in order to distinguish the in-phase and in-quadrature part of the electromagnetic signal after demodulation.

The table 2 gives the list of the nominal and simulated range of variation for considered parameters of the pipe.

Parameter	Nominal value	Simulated values
Steel sheet thickness	2 mm	0.2 / 0.5 / 0.8 / 1.5 / 2 / 2.5 / 3 (mm)
Thickness of the layer of concrete "Lift-off"	36 mm	25 / 30 / 35 / 36 / 40 / 45 (mm)
Relative steel permeability	1 000	500 / 1 000 / 1 500 / 2 000
Conductivity	6.10^6 $S.m^{-1}$	5 / 6 / 7 (.10^6 $S.m^{-1}$)
Probing frequency	-	10 / 5 000 (Hz)

Table 2: Dimensional simulated parameters

The Eddy Current module of CIVA does not include the modelling of the reinforcement structure. Thus, the simulation is performed considering a pipe without reinforcement.

Steel sheet thickness and lift-off influence

The permeability μ_r and the conductivity σ are set to their nominal values.

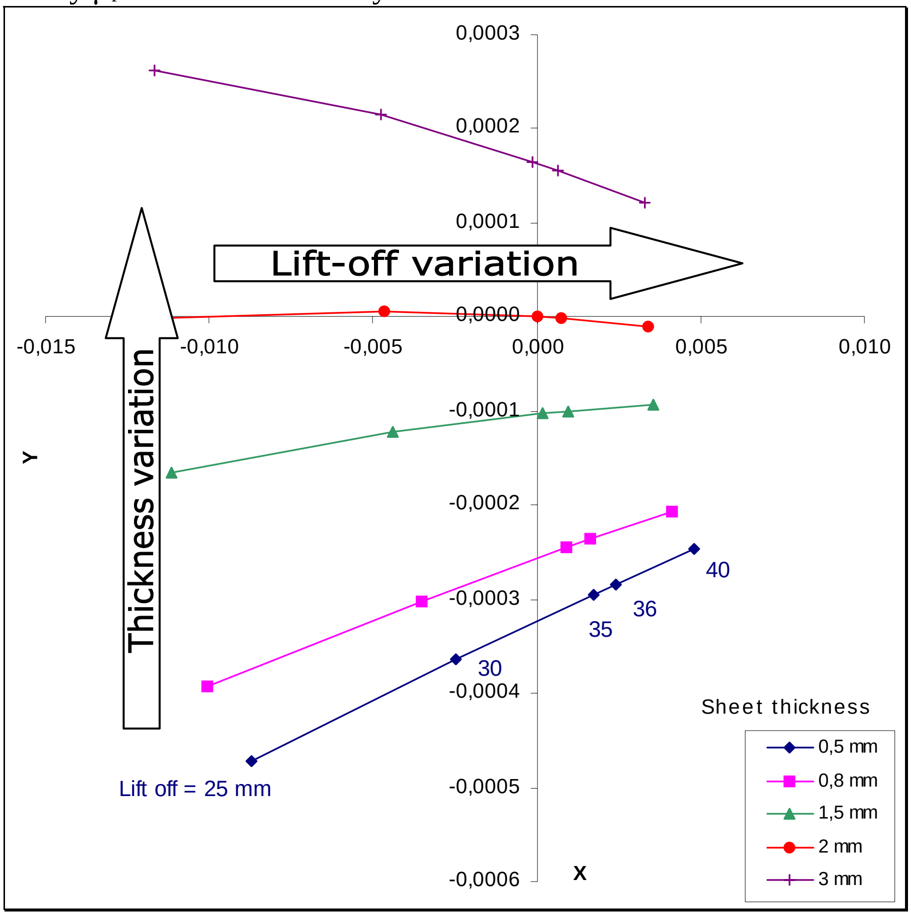


Fig. 1: B_z (µT) as a function of residual thickness *e* and lift-off *E* at f=10 Hz

Each solid curve represents one value of the steel sheet thickness and each point a different value for the lift-off (i.e. thickness of the concrete).

The Fluxgate responses to the steel sheet thickness variations and to the concrete layer thickness variations have different phases in the complex plane, which is a necessary condition for the separation of the two variables which are the unknown of the inspection. The phase lag is close to 90°, which helps greatly to the separation and to the evaluation of the two parameters.

Conductivity and permeability influence

The considered values for simulation are:

- for conductivity: 5, 6 and 7 (10^6 $S.m^{-1}$),
- and for relative permeability: 500, 1000, 1500 and 2000.

Modelling calculation permits to conclude that the permeability influence on the Fluxgate signal is weak compared to the effect of the steel sheet thickness.

Conductivity's one is more important. Nevertheless, as its range of variation is small, its influence on the Fluxgate signal is weak.

Therefore, the variation of conductivity and relative permeability due to steel grade dispersion have an overall small effect on the measurement method.

The discrimination between two sheets thicknesses of 0.5 mm and 2 mm can be done easily in spite of the variations of μ_r and σ.

Corrosion effect

The corrosion effects were simulated by introducing into the model an oxide coating (layer with a very low conductivity).

The sheet is divided into two zones: an internal zone (inner of the steel sheet which thickness is noted e_{int}) and an external zone which thickness layer is noted e_{ext}. The removing of samples of pipes affected by corrosion was used to evaluate the increase in thickness of the metallic sheet due to corrosion. This variation of the corroded metallic sheet is also simulated with CIVA.

e_{int} (mm)	σ_{int} (.10^6 S.m^{-1})	e_{ext} (mm)	σ_{ext} (.10^6 S.m^{-1})
0,5	0,001	1,5	6
1	0,001	1	6
1,5	0,001	0,5	6
2	0,001	0	6
3	0,001	0	6
4	0,001	0	6

Table 3: Studied parameters simulating corrosion (variation of thickness and conductivity)

The modelling of the corrosion layer shows that it has an effect on the signal B_z similar to a sheet thickness reduction. The phenomenon of sheet thickness increase due to a captive layer of oxides between the base material and the layer of concrete implies an increase in the imaginary part of B_z but insufficient to reach the value of a healthy sheet of 0.5 mm.

Lift-off measurement at f=5 kHz

The objective of this simulation is to check that a high frequency can be used to measure the lift-off, E, while being insensitive to the influence of a variation in the sheet thickness. The values of the studied parameters are identical to preceding simulations.

At 5 kHz, the sensor is not sensitive to the sheet thickness variation (small standard penetration depth: δ=0.09 mm). The influence of μ_r and σ is observed in a phase angular sector different to the lift-off one. The lift-off contribution on the Fluxgate signal is separable from the other parameters. The frequency of 5 kHz is thus appropriate for a lift-off (E) measurement while being not sensitive to the sheet thickness influence.

Experimental tests

The simulation results proved the feasibility of the thickness measurement of a steel sheet with various lift-off and others perturbation parameters such as variation of steel grade and presence of embedded oxides. They must however be checked by experimental tests and be completed by tests taking into account the external concrete reinforcement. Some laboratory tests were thus undertaken. The pipe diameter is relatively large (d_{ext}=730 mm) compared to the driving coil dimensions (about 5 mm). Therefore, the pipe surface is considered as planar. This approximation is representative of many industrial geometries and largely facilitates the realization of laboratory tests. Influent parameters are:

- e: steel sheet thickness,
- E: lift-off,
- steel grade (relative permeability μ_r and conductivity σ),
- f: frequency of excitation,
- the reinforcement and its position.

Experimental tests without reinforcement

On planar mock-up

A first series of tests without considering the reinforcement bars were carried out on a planar mock-up.
μ_r and σ values are intrinsic to the considered metallic sheet used in the mock-up. In order to vary the other parameters and to observe their influence, we used:

- steel sheets of different thickness: 0.5/0.8/1.5/2/2.5/3 mm,
- sheets of Plexiglas (PMMA) of various thickness: 2/5/8/10 mm, which model the concrete layer.

The following measurement instruments were used:

- a function generator,
- a current amplifier,
- a Lock-in amplifier (synchronous detection).

The sensor for the vertical magnetic induction is the micro-Fluxgate. Magnetometers of the Fluxgate type are instruments used to measure the vector components of a magnetic field. Their typical measuring range in sensitivity extends from 0.1 nT to approximately 1 mT and their frequency range vary from static fields to a few kHz. The sensitivity of the fluxgate used was 100 mV.µT^{-1}. The CEA LETI developed this integrated Fluxgate [2]. The diagram in Fig. 3 illustrates the Fluxgate operating principle.

The micro-Fluxgate design is patented by CEA.

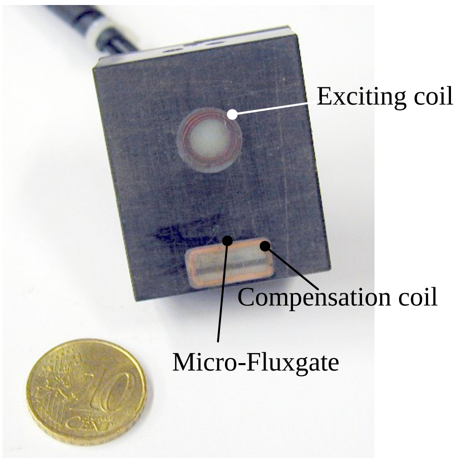


Fig. 2: Fluxgate sensor (sight from below)

The results obtained during the tests are plotted in the complex plan. A first series of tests <u>without</u> reinforcement was carried out in order to consolidate the results of simulation. The Fig.3 presents the experimental setup diagram.

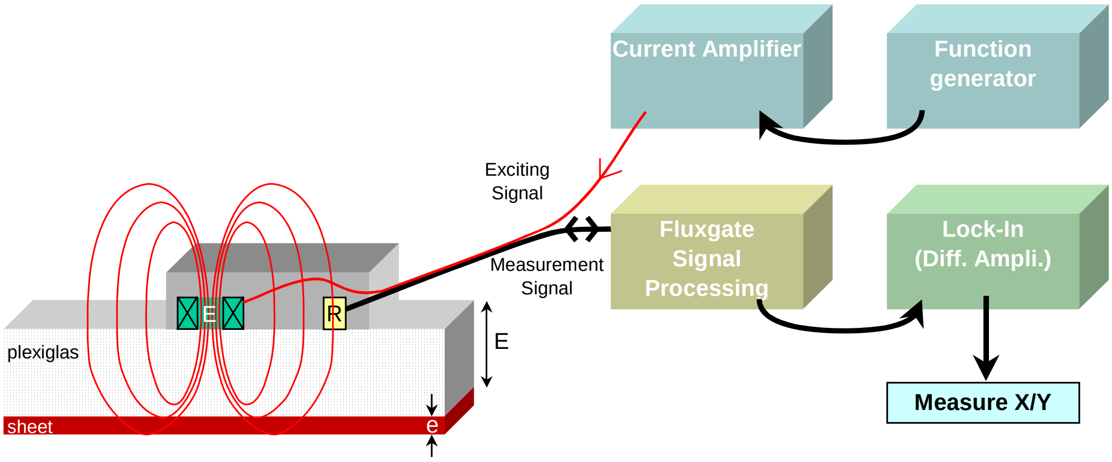


Fig. 3: Diagram experimental setup without reinforcement

The values of the parameters studied are given in table 4.

Sheet thickness e (mm)
0.5
0.8
1.5
2
3

Lift-off E (mm)
25
30
35
40

σ and μ_r
Fixed by studied sheet

Table 4: Values of influent parameters studied during the tests

The results of the first series of tests are plotted in the Fig. 4.

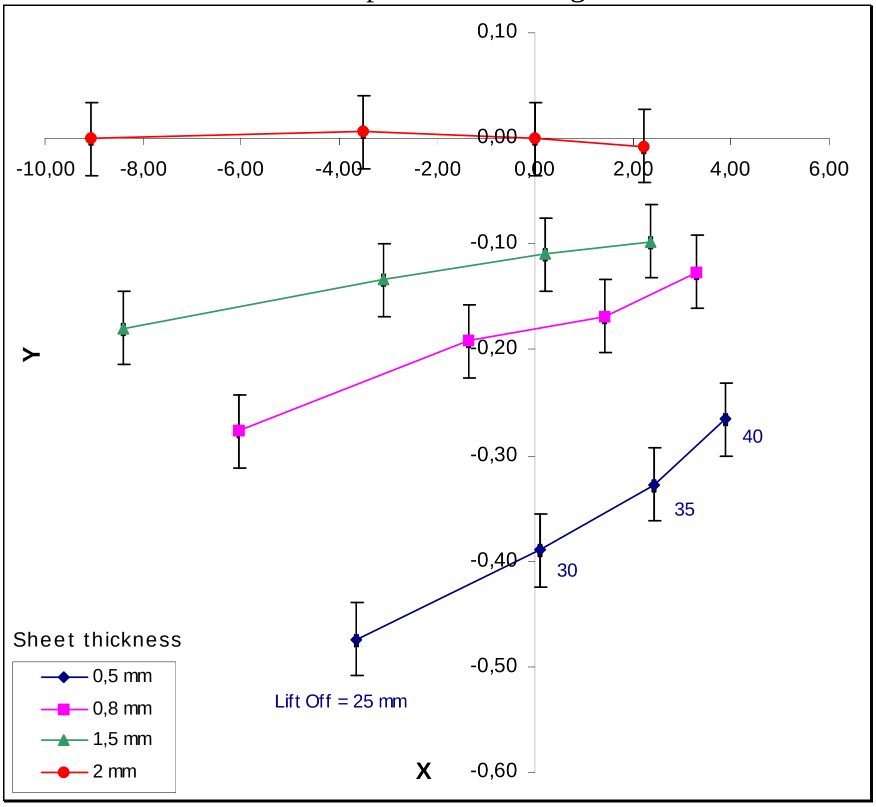


Fig. 4: Measurement of B_z as a function of the thickness and Lift-off, f=10 Hz, without reinforcement

Each solid curve corresponds to a certain sheet thickness and each point on a curve to a different lift-off. The error bars plotted on the curves, are the result of a series of repeatability measurements. The effect of the thickness and of the lift-off variations on the signal comes with 2 different phases. The variation of the signal along the Y-axis is 29 dB weaker than according to the X-axis. That is the reason why a current amplifier is used. The experimental results are in agreement with the simulation performed with CIVA. Such results validate the feasibility of the steel sheet coated thickness measurement without reinforcement bars. The constitution of an abacus would be a solution allowing the inversion of the data and thus the thickness determination. The first series (without reinforcement) having given positive results, a second sequence of tests was carried out, with the reinforcement bars.

On real pipe

Experimental tests were also done on a real pipe from inside (inner concrete layer is not reinforced). The Fig. 5 presents the results.

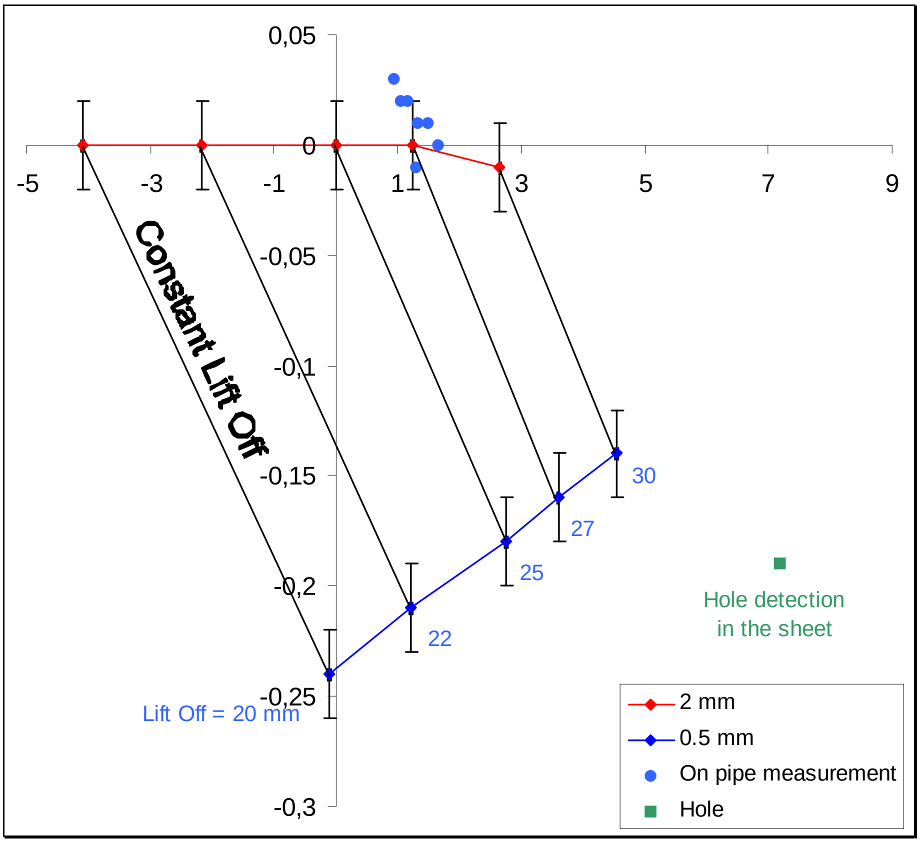


Fig. 5: Measurement of B_z as a function of thickness and Lift-off, f=10 Hz from the inside of the pipe

A measurement of the thickness sheet was done with a slide caliper. This measurement gives e=2.2 mm ± 0.1 mm. The measurement of the lift-off gives E= 27.2 mm ± 1 mm. The experimental measurements are represented by blue points on the Fig. 5. The lift-off measured by the Fluxgate corresponds to the one obtained with the slide caliper. The measured thickness is also identical to the actual thickness. The reinforcement bars located on the other side of the steel sheet seems to have no or negligible influence on the measurement method.

With reinforcement experimental tests

The instrumentation is the same one as during the tests without reinforcement. The Fig. 6 gives the experimental setup diagram.

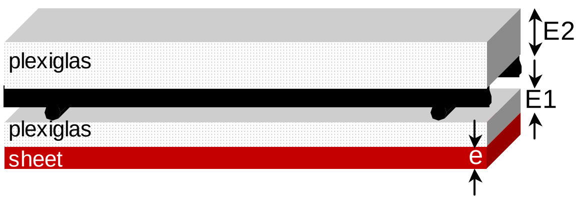


Fig. 6: Experimental setup diagram with reinforcement

The thickness of the steel sheet is noted e, the lift-off above reinforcement E2 and the thickness of the concrete layer below reinforcement is noted E1.

The steel sheet is a square slab of 500 mm on side. The reinforcement is made of cylindrical steel bars of 6 mm in diameter. The total thickness of the reinforcement layer is 13 mm. During tests with reinforcement, the sensor was positioned between two consecutive transverse wire of the reinforcement and on a Plexiglas sheet (E1), as shown on Fig. 7.

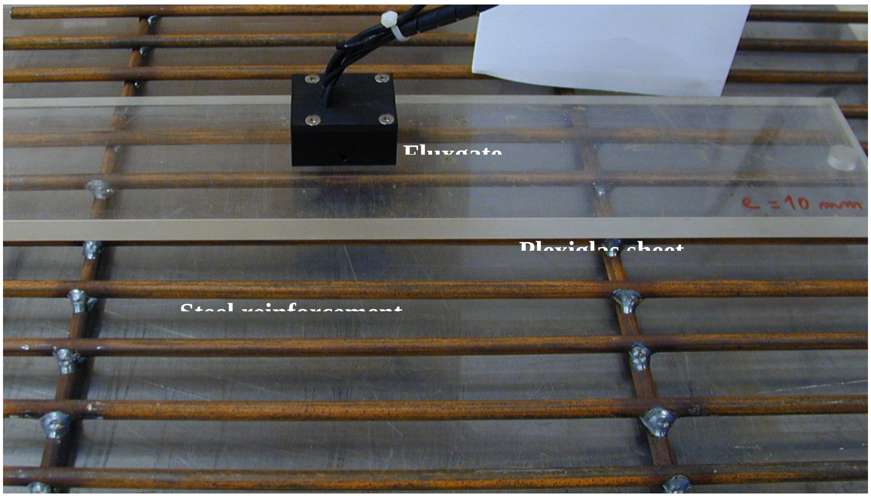


Fig. 7: Fluxgate sensor on plane experimental setup

The reinforcement structure is now taken into account. The test is representative of a realistic inspection configuration for an operator located nearby the pipe. The outside inspection configuration allows nominal operation of the pipe which is of great importance for the utility.

The results show that information on the steel sheet thickness and variable manufacturing concrete thickness layer remain separable but that the analysis of the signals is complex. The presence of the reinforcement bars deviates the lines of the electromagnetic field and affect the measurement to a significant extent. The position of the reinforcement bars in the depth of the concrete layer has a significant impact on the results of measurement. It is therefore advisable to detect beforehand by ET the position of the reinforcement bars in order to have a better estimate of the overall thickness of the metallic sheet.

The discrimination between two sheets of different thickness, namely 0.5 mm and 2 mm, remains however realizable. Obtaining a very good accuracy will be difficult but an important loss in the metallic sheet thickness will be detectable in the framework of a maintenance program.

Conclusions

A first series of tests without reinforcement bars was carried out producing conclusive results. The correlation between simulation and the tests is very good.

The presence of the reinforcement bars in the concrete modifies the outcomes of the measurement, which has to be corrected. A previous evaluation of the position of the reinforcement bars using ET seems to be necessary in order to correctly analyse the measurements.

We have shown that it is possible to separate for the Fluxgate signals the contribution due to the variation of the metallic sheet from the variation of the thickness of the concrete layer due to dispersion in the manufacturing process. The level of the signals relevant for the evaluation of the thickness of the sheet is however 29 dB weaker than the signals due to the variation in the layer of concrete surrounding the metallic sheet .

Taken these considerations into account, the discrimination between a zone with 0.5 mm thickness sheet and a zone with a 2 mm thickness sheet, is possible.

This study based on the development of a NDT method backed by simulation work using CIVA and completed by an experimental evaluation has allowed us to establish the feasibility of the determination of the thickness reduction of a sheet steel coated pipe by means of an electromagnetic measurement method.

The next step for an industrial application of the method is to build an abacus for the inversion of data (separation of the sheet thickness parameter from the concrete layer - lift-off - parameter). The algorithm for the automatic processing of the data will then have to be developed and benchmarked.

References

http://www-civa.cea.fr

J.M. LEGER, T. THOMAS, D. DURET, H. JOISTEN, H. SIBUET, P. GAUD, J.M. FEDELI – Integrated Microfluxgate Study an Characterization – LETI (CEA-Grenoble / Technologies Avancées)

http://www.bonnasabla.com

S. Vorojtsov – Calculation of the Various Contributions from Magnetic Material – Status of the Dubna B-field activity – Joint Institute for Nuclear Research, Dubna, Russia – Meeting on ATLAS magnetic field, 25th February 1999, CERN

Technique de Contrôle Non Destructif par Courants de Foucault (Eddy Current Non Destructive Testing) – Support de formation – CEA LCME

A. May, D. L. Atherton – Multi-frequency electromagnetic inspection of pre-stressed concrete cylinder pipe – Insight Vol. 44 No 2 February 2002

P. Gaydecki, I. Silva, B.T. Fernandes, Z.Z. Yu – A portable inductive scanning system for imaging steel-reinforcing bars embedded within concrete – Department of Instrumentation and Analytical Science, UMIST – Sensors and actuators 84 (2000)

James E. LENZ – A review of magnetic sensors – Proceedings of the IEEE, Vol. 78 No 6 – June 1990