- Technical Paper -

DEVELOPMENT OF TESTING PROCEDURE FOR MAGNETIC FLUX LEAKAGE BASED METHOD OF CORROSION DETECTION FOR REINFORCEMENT IN POST-TENSIONED CONCRETE STRUCTURES

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ABSTRACT

The presented paper discusses the basics of application of magnetic flux leakage method in testing of reinforcement steel bars of post-tensioned concrete structures. Magnetic flux leakage method utilizes magnetic properties of reinforcement steel bars and influence of various defects on their magnetic properties. Currently, magnetic flux leakage method is mainly used to detect ruptures of reinforcement steel bars in concrete. The proposed method of processing of magnetic flux leakage signal allowed to reliably detect presence of corrosion and establish its position on a specimen.
Keywords: Non-destructive testing, Magnetic flux leakage, Steel corrosion, Post-tensioned concrete, Signal processing.

1. INTRODUCTION

Corrosion of reinforcement steel bars in concrete is a dangerous process, leading to deterioration of concrete structures. Details about the mechanism of corrosion can be found in literature [1], but, generally, its detrimental action comprises a formation of corrosion products in transitional zone between concrete and a reinforcement steel bar, which results in spalling of concrete cover. Another dangerous effect of corrosion is a decrease of cross-section of reinforcement steel bars. Therefore, results of corrosion action are big expenses for maintenance, renovation and repair of concrete structures and, in severe cases, corrosion can lead to structural failure.

In turn, post-tensioned concrete (PC) structures, as they contain prestressing steel bars, which are constantly subjected to big tension loads, will be more sensitive to even small decrease of cross-section, which makes corrosion in that case even more dangerous.

Therefore, in the case of PC structures, timely detection and evaluation of corrosion is of big interest. Non-destructive testing (NDT) methods are widely used for that purpose. However, electrochemical testing methods, which nowadays are the most widely implemented methods of NDT for corrosion of reinforcement steel bars in concrete, possess several limitations. In particular, they do not allow to obtain information about degree of corrosion in terms of a decrease of a cross-section or a weight-loss and they are influenced by temperature, humidity and quality of electric contact with reinforcement steel bars [2].

Magnetic flux leakage (MFL) method can be a promising solution for the problem of corrosion detection for prestressing steel bars in PC structures. The method is successfully used in many industries, related with quality control and inspection of steel products for decades, including detection of corrosion-related damage [3, 4]. Also the method is reported to be effective in detection of rupture of reinforcement steel bars of concrete structures [5-7].

One of the big advantages of MFL method in a case of its application in concrete is the fact, that regular concrete doesn't have magnetic properties and therefore doesn't have any influence on the results.

Basing on theoretical fundamentals and history of successful application of MFL method, it is possible to presume that it will be effective for detection of corrosion of prestressing steel bars of PC structures.

Thus, the aim of the presented study is to develop a technique of corrosion detection for prestressing steel bars of PC structures using MFL method.

2. DESCRIPTION OF MFL METHOD AND PROPOSED TESTING PROCEDURE

2.1 Basics of MFL method

Basically, MFL method consists of an application of magnetic field to the tested ferromagnetic object and consequent scanning of it with sensors of various types.

Two general types of scanning techniques are used. The first is active field scanning, which usually implies use of electric magnet for magnetization; scanning is carried out in active magnetic field. In that case, the procedure requires constant electric supply, which makes a device quite heavy and big. A detailed description of such a device may be found in the literature [8].

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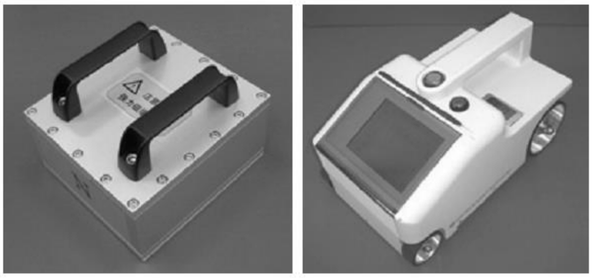
Devices operating in remanent filed belong to the second type. The measurement are carried out after switching off an electric magnet or with a use of a permanent magnet, made from special magnet alloy. The device used for experiments in the presented study – M-EYE testing tool (see Fig.1) – also belongs to the devices, operating in remanent magnetic field. It consists of a permanent magnet and scanning unit with two coil-type sensors. The device is light-weight and doesn’t require supply of electricity. More detailed information about M-EYE testing tool can be found in the study of Makoto Hirose et al. [9].



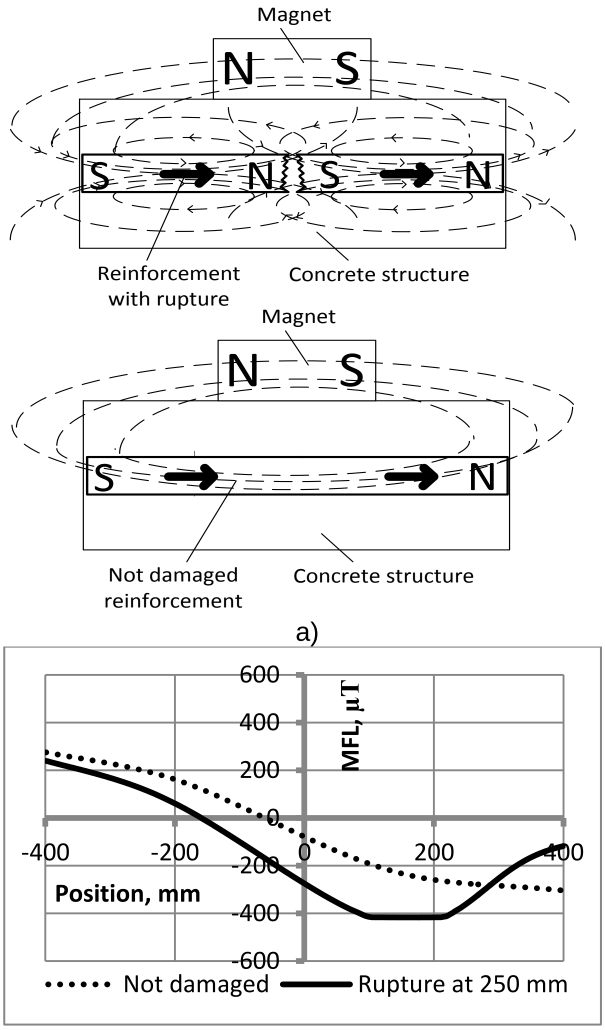
a) b)

Fig.1 – M-EYE MFL testing tool:
a) Permanent magnet
b) Sensor unit

In a case of a detection of rupture or deep narrow defect (cracks, cuts etc.) of reinforcement steel bars, MFL method utilizes the mechanism of formation of additional magnetic poles in a place of the defect, which results in a distinct peak of signal in a vicinity of that point, which, in turn, makes it possible to detect that defect. That case is illustrated in Fig.2 on an example of a reinforcement steel bar of d=19 mm with rupture and without it (other conditions of testing are the same). As it can be seen, there is a clear plateau in a vicinity of a rupture (presence of the plateau instead of peak is related with measurement limits of the sensors of MFL sensor unit).

In the case of corrosion of PC structures’ prestressing steel, resulting rupture can lead to very dangerous consequences (including structural failure), therefore, it is necessary to detect deterioration of prestressing steel bars before the rupture. Moreover, in the case of PC prestressing steel bars, even a small decrease of cross-section can cause rupture, because PC concrete prestressing steel bars are subjected to tension load in addition to structural load. It results in higher requirements for sensitivity of MFL method, which can’t be achieved by means of using additional pole formation mechanism, similar to the case, demonstrated in Fig.2, because additional magnetic poles don’t form in a case of shallow cracks or corrosion pitting.

In that case, the following mechanism can be used. It is known, that MFL is proportional to the weight of object [10]. In a case of corrosion, which is accompanied by loss of weight of corroded reinforcement steel bars, a change of weight and, therefore, signal change can be used as an indicator of the presence of corrosion. That case is illustrated in Fig.3 on an example of two reinforcement steel bars with different diameter (13 mm and 19 mm) and, therefore, weight (other conditions of testing are the same). It is clear that lighter object produces less intensive signal.



b)

Fig.2 – MFL testing of a ruptured reinforcement steel bar and a not damaged reinforcement steel bar:
a) Scheme
b) MFL testing results

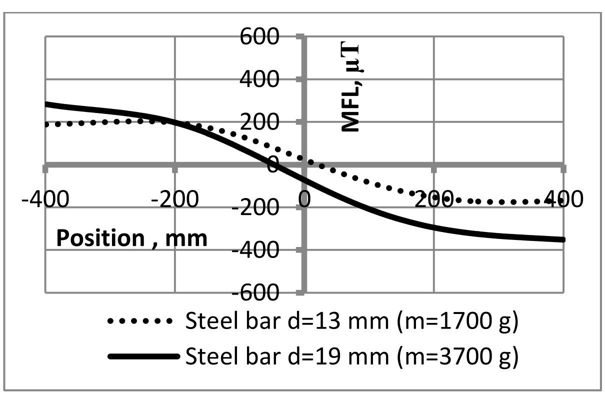
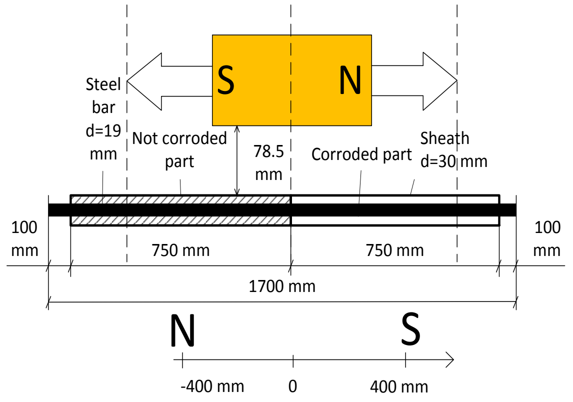


Fig.3 – Results of MFL testing of steel bars with different weight and diameter.

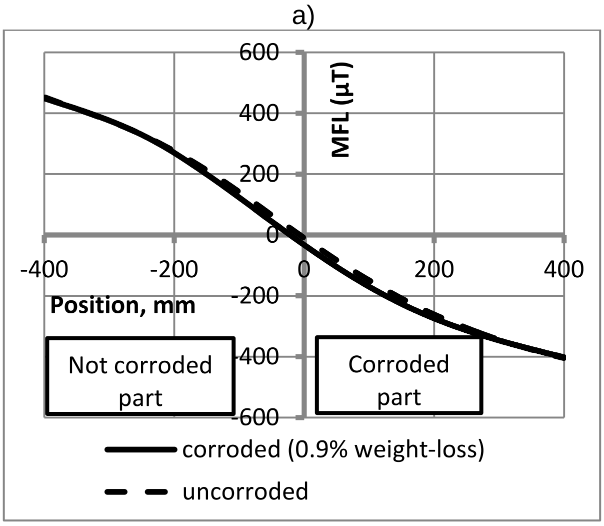
2.2 Results of preliminary experiments

The previous experiments demonstrated that MFL method is capable to detect corrosion of steel bars inside metal sheath in the experiment, which was simulating partial corrosion of a steel bar in PC structures [11].

However, obtained results (see Fig.4) had several disadvantages. First, small difference in signal between corroded and not corroded specimens made it hard to clearly detect corrosion. Second, the position of the corroded part was unclear.



a)



b)

Fig.4 - Study of corrosion of steel bars inside metal sheath by MFL (adopted from [11]):
a) Experiment setup
b) Results of the experiment

In order to solve aforementioned problems, it was decided to develop improved procedure of scanning and processing of signal.

2.3 New procedure of scanning and processing of signal

The previously used procedure for scanning and signal processing comprised scanning of a whole specimen in one pass, with one magnetization and one scan (Fig.4a). In that case, raw signal (i.e., unprocessed signal) was used for corrosion detection. That method is successfully used for a detection of ruptures, but shows insufficient sensitivity in a case of corrosion damage (see Fig.2 and Fig.4b for comparison of those cases).

The proposed new procedure is quite different from the previous one and comprises the following main points:

1. Tested object is divided into several overlapping sectors.
2. Each sector is magnetized and scanned separately.
3. Derivative parameter of signal (area confined by signal curve) is used instead of raw signal.

Let's illustrate the application of the proposed procedure on an example of the specimen from the previous experiment (see Fig.4a). The scheme of the scanning procedure, for the case of the specimen from the previous experiment is presented in Fig.5. The steel bar inside metal sheath is divided in 5 sectors, after that they are magnetized and scanned separately.

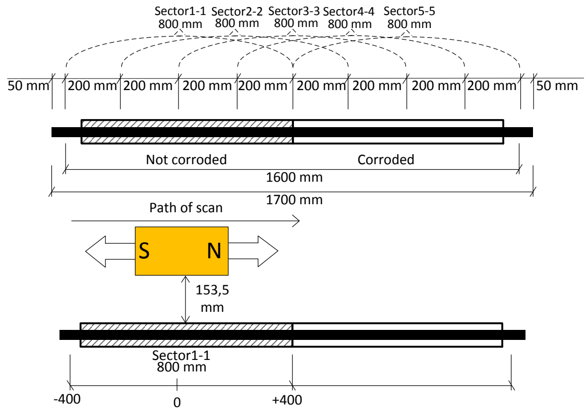


Fig.5 – Scheme of new scanning procedure.

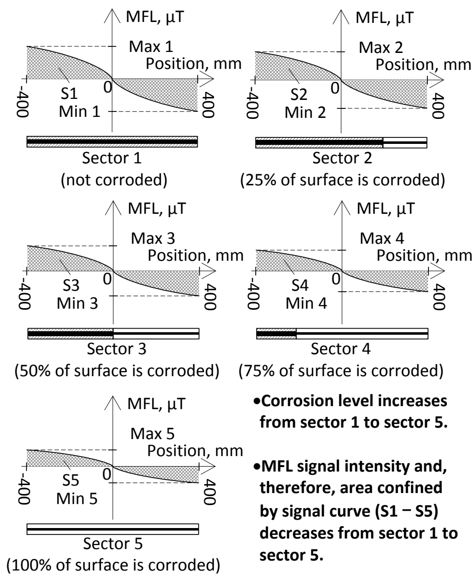


Fig.6 – Scheme of change of MFL signal intensity due to change of corrosion level in sectors 1-5 of the specimen.

Following justification can be given for the proposed scanning procedure. First, a division of a specimen in sectors and separate magnetization is favorable, because it increases the level of magnetization and, consequently, a possible MFL signal from defects.

Use of derivative parameter is justified by the following. It is known that corrosion, resulting in corrosion weight-loss, leads to a decrease of weight in corroded part of reinforcement steel bars. As it was demonstrated before (see Fig.3), lighter objects produce less MFL, therefore, signal curve has smaller extremums and area, confined by that curve, is smaller (see curves for steel bars with different weight in Fig.3). Thus, in a case of the specimen, presented in Fig.5, the level of corrosion will increase from sector 1 to sector 5, and, at the same time, level of MFL will decrease from sector 1 to sector 5. That example is illustrated in Fig.6.

As a result of magnetization and scanning of all 5 sectors of the discussed specimen 5 raw signal curves are obtained (Fig.7).

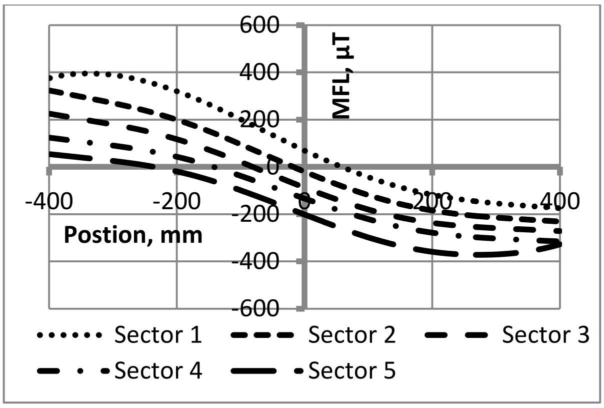


Fig.7 – Raw signal obtained by the proposed procedure.

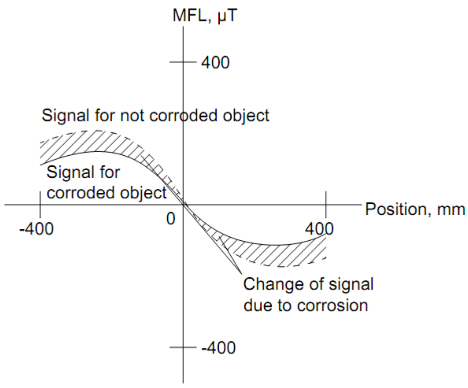


Fig.7 – Change of area, confined by MFL signal curve due to corrosion.

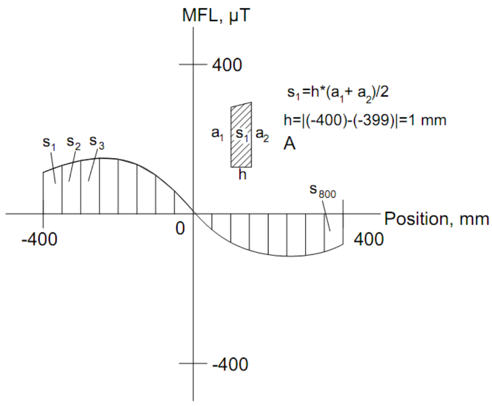


Fig.8 – Scheme of application of trapezoids method in the discussed case.

The presented raw signal doesn't give much information about the presence of corrosion. Also, in regard with Fig.7, it is worth mentioning that comparatively high levels of MFL signal for sector 1 and sector 5 (which correspond to the ends of the tested object) are related with presence of induced magnetic poles at the ends of the tested object.

In the proposed procedure derivative parameter of signal is used, namely, area confined by MFL signal curve. As it was explained above, area, confined by MFL signal curve is subjected to a decrease due to corrosion-related change of the tested object's weight (see Fig. 6). Numerical assessment of area confined by the curve can be conducted by means of method of trapezoids. That method consists of dividing the area, confined by the curve in a series of trapezoids, which total area will be equal, with an acceptable level of accuracy, to the area confined by the curve (see scheme in Fig.8). The Eq.1 is used for that purpose:

$$S = \sum s_i \qquad (1)$$

where,

S :total area confined by the curve, mm*µt.

s_i :area of a single trapezoid, mm*µt.

i : number of trapezoids.

Area of single trapezoid can be easily calculated using basic equation for area of trapezoid, because the provided raw data allows it. See Table 1 for example of raw data, provided by M-EYE testing tool, and Fig.8.

Table 1 Example of raw data, provided by M-EYE testing tool

Position from the starting point of scan path, mm	Position considering the center of scanned section, mm	MFL, µT
1	-400	a1
2	-399	a2
3	-398	a4
…	…	…
800	400	a800

*a1…a800 – symbols representing values of MFL.

As a result of an application of the proposed procedure a series of 5 values of areas confined by MFL signal curves (S) for sectors 1…5 are obtained. Difference between areas, confined by MFL signal curves, can be used as an indicator of corrosion damage, as it was explained above (see Fig.6).

The following part of the paper contains the experimental study of the proposed procedure.

3. MATERIALS AND METHODS

Basically, specimen design and corrosion exposure conditions are the same to those, which were used in the previous studies (see Fig.4a) [11].

3.1 Specimens

Specimens were fragments of metal sheath d= 30 mm with a steel bar d=19 mm inside. Length of bar was 1700 mm, length of sheath was 1500 mm. Half of sheath was filled with a grout to protect metal bar from corrosion. Before the fabrication, a half of bar which was supposed to be grouted, was covered with an adhesive tape to protect from electrochemical corrosion.

3.2 Exposure conditions

Fabricated specimens were subjected to accelerated corrosion by impressed current method. Method is based on a connection of a specimen to a power supply with a positive terminal connected to a steel bar and negative terminal to a sheath. Before a connection of a power supply, a half of sheath which was not grouted was filled with 3% solution of NaCl and sealed. After turning on a power supply, the electric current starts to flow from a positive terminal (a steel bar) to a negative terminal (a sheath), thus making a steel bar an anode and a sheath a cathode, which leads to corrosion of a steel bar.

Two specimens with designed corrosion weight-loss equal to 6% and 8% were fabricated.

3.3 Measurements

Prior to the fabrication, of specimens, the weight of steel bars and their diameter were measured.

After fabrication and achieving designed level of corrosion, specimens were tested with MFL method using the procedure described earlier in section 2. Distance between tested object and the sensor was increased on 75 mm as compared to the previous studies (see Fig.4) and was equal to 153,5 mm (see Fig.5). All measurements were repeated 3 times to avoid errors. The presented results are an average value of those 3 measurements.

After testing specimens by MFL method, specimens were cut, corroded bars were extracted. After that corroded parts of bars were immersed in 10% solution of heated up to 60^0C diammonium hydrogen citrate $(NH_4)_2HC_6H_5O_7$ for two days in order to remove corrosion products. Then bars were measured and weighted, thus, obtaining actual weight-loss values.

4. RESULTS

4.1. Weight-loss measurements results

After MFL testing of corroded specimens, it was established that achieved weight loss was equal to 5.62% (for 6% specified) and 8.68% (for 8% specified).

4.2. MFL measurements results

Results of MFL testing for specimens with 8.68% and 5.62% corrosion weight-loss, obtained using new testing procedure are presented in Fig.9 and Table 2. Results for not corroded specimen are presented for comparison. Marks of the lines in Fig.9 represent calculated values of S, as it was explained above (see section 2.3). The testing and calculation of a certain S value for Fig.9 consists of the following steps: division of the specimen in 5 sectors, separate magnetization and scanning of each sector, calculation of area confined by MFL curve (S) for each sector. Each S value in Table 2 is an average of 3 measurements (standard deviation of measurements is presented in Table 2 under the S value in parentheses). Table 2 contains only final values of S, because complete calculation is too voluminous (each S value is a sum of about 800 s_i values).

Table 2 Results of calculation of area confined by curve (s) for Fig.9.

Specimen	Area confined by MFL signal curve, $S*10^3$, mm*μT				
	Sector 1	Sector 2	Sector 3	Sector 4	Sector 5
Not corroded	83,9 (±1,7)	84,6 (±2,7)	75,5 (±1,6)	69,4 (±1,5)	81,8 (±2,1)
5,62% weight-loss	85,3 (±2,2)	84,7 (±2,4)	74,8 (±1,1)	65,4 (±2,9)	76,8 (±2,3)
8,68% weight-loss	82,8 (±1,7)	84,6 (±1,0)	73,9 (±1,1)	62,7 (±1,9)	70,4 (±2,4)

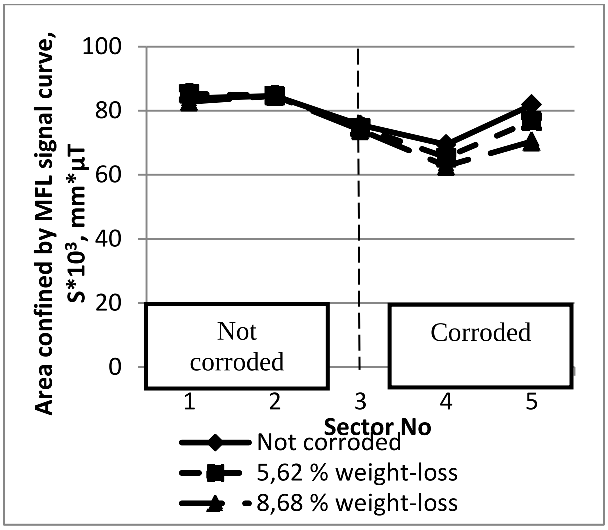


Fig.9 – Results of an experimental application of the proposed procedure of MFL testing for the specimens with different levels of corrosion damage.

From the graph it can be seen that there is a clear difference between the not corroded specimen and the corroded specimens. Moreover, resulting curves in the not corroded area for corroded specimens and not corroded specimen almost coincide, but in the corroded area there is a clear difference between the corroded specimens and the not corroded specimen.

Values of the derivative parameter of the signal (area confined by MFL signal curve, S) tend to decrease in the corroded part of the specimen with an increase of level of corrosion, which proves, that MFL signal will gradually decrease with an increase of weight-loss in the scanned sector (see Fig.6).

5. DISCUSSION

The obtained results show, that the presented method seriously improves readability of the results, in comparison with the raw signal. For comparison, Fig.10 presents raw signal (for sector 3) for the same test as discussed in section 4 of the paper.

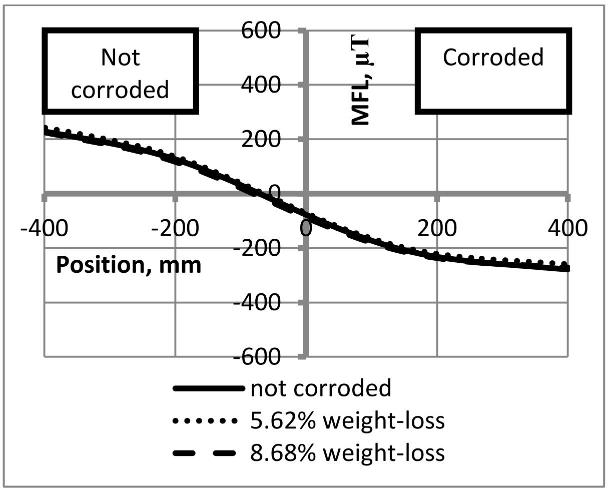


Fig.10 – Raw signal for different levels of corrosion damage.

Another question that requires clarification is a shape of the curve in Fig.9. In particular, a tendency of values of areas, confined by curves of respective sectors, to decrease in a direction of right (corroded) side (from the sector 2 to the sector 4), even in a case of the not corroded specimen and a tendency of the parameter to increase from the sector 4 to the sector 5.

That effect can be explained by two factors. First, it is a type of used magnetization pattern. As it can be seen from Fig.5, scanning starts from the sector 1, where the induced magnetic pole is located, magnetic pole, in turn, produces the strongest MFL. Along with moving away from the pole, intensity of MFL is decreasing while scanning moves from sector 1 to sector 4, and backwards, MFL is increasing with scanning is getting closer to sector 5, where another induced magnetic pole is located. That's why the curve on Fig.9 has the concave-like shape, even in a case of the not corroded specimen. Second, there is a certain asymmetry of signal, which probably related with the features of the used magnet. As it can be seen on the graphs, representing raw signal (Fig.2,3,4b,10), there a certain difference between right and left sides of the graph even in a case of the not corroded specimens, which signal is supposed to be of the same shape in the left and right sides. That feature was observed in all test results and that's, presumably, the reason for the shape of the processed signal curve as well.

6. CONCLUSION

Following conclusion can be made on the present stage of the study:

1. New procedure of scanning and processing of MFL signal is developed and its efficiency is experimentally proved.
2. The developed procedure allows to clearly detect presence of corrosion weight loss of 5.62% and more at the discussed experiment conditions.
3. The developed procedure allows to differentiate between the levels of corrosion weight loss.
4. The developed procedure allows to establish the location of the corroded site.

In general, the presented results lay a foundation for a development of the MFL method for corrosion detection for reinforcement steel bars and prestressing steel in PC concrete using M-EYE testing equipment.

However, further studies are necessary to make the MFL method for corrosion detection fully functional.

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