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Impact of the Effort of a Reinforced Concrete Element on the Results of the Reinforcement Corrosion Risk Tested Using the Galvanostatic Pulse Method

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ABSTRACT

Diagnostics of existing buildings includes, among others research to assess their durability. In the case of reinforced concrete structures, such tests include semi-destructive electrochemical tests to forecast the corrosion risk of steel bars in concrete, and one of the methods used is the electrochemical, polarizing galvanostatic pulse method. The aim of the article was to recognise the influence of element effort on the measurement results obtained with this method. For the tests, a reinforced concrete cantilever slab loaded monotonically was used. During the tests, the stationary potential and corrosion current density of the main reinforcement bars, as well as the resistivity of the concrete cover, were measured. On the basis of the results obtained, it was found that the level of effort on the element affects the values of the measurements performed. Differences in the values of measured parameters at different levels of element effort are sometimes so large that they may significantly affect the conclusions about the corrosion risk of the tested reinforcement, and thus incorrectly estimate the durability of the tested element.

Keywords: construction diagnostics, assessment of the durability of a reinforced concrete element, element effort, semi-destructive galvanostatic pulse method.

INTRODUCTION

Non-destructive testing is an important part of the diagnostics of reinforced concrete structures [1–3]. They are of great importance especially in situations where the tested object is continuously operated and is therefore under load during the tests [4–6]. Tests performed on the facility usually include: assessment of concrete damage (scratches, cracks, efflorescence), adhesion between concrete and reinforcing steel, material testing (physical and strength parameters), as well as displacements in structure elements [7–9]. Tests are also performed to estimate the durability of elements based on the estimation of the corrosion risk of concrete and reinforcement in representative areas [10, 11]. For this purpose, non-destructive or semi-destructive electrochemical methods are used in particular[12–14]. The use of electrochemical research techniques is related to the specificity of corrosion development on steel rods in concrete. Such a rod (which can be considered a type I conductor) can be treated as an electrode, and the alkaline liquid which fills the pores in concrete as an electrolyte. If small defects appear on the surface of the rod, cathodic and anodic areas are created and a kind of galvanic microcell is created in which ions flow in the electrolyte and the steel rod conducts electrons (Fig. 1).

On the basis of the process described above, semi-destructive testing methods have been created to assess the progress of steel corrosion in concrete. These tests involve measuring selected electrical parameters and comparing them with appropriate criterion values. The measurements include: stationary potential of the reinforcement, resistance of the concrete cover and corrosion current density. The essence of measurements using electrochemical methods is the polarisation of the reinforcing bar, i.e. causing a current to flow in

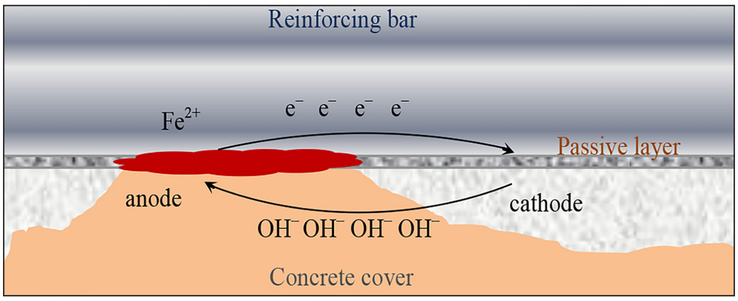

Figure 1. Electrochemical corrosion process of reinforcement in concrete

the cell, which is a steel bar embedded in concrete with pores filled with liquid, i.e. disturbing the dynamic balance of the corrosive agent system by generating a current of a specific intensity (electric impulse) and then measuring the afore-mentioned electrochemical parameters caused by this disturbance (in particular the corrosion current density). Depending on the method of generating the pulse, various polarisation methods have been developed (described, among others, in [3]), including the galvanostatic pulse (GP) method [12].

Due to the specificity of conducting measurements using the GP method, in which the values of the diameter and length of the tested bar are essential, as well as the fact that stresses in the steel may cause a change in these values, it seems important to recognise the influence of element effort on the obtained measurement values. Therefore, the authors decided to investigate this relationship experimentally, especially since they have not found any publications on this subject yet.

GALVANOSTATIC PULSE METHOD

The galvanostatic pulse technique is used to assess the level of advancement and the risk of corrosion of reinforcement in reinforced concrete elements. One of the devices designed to perform polarisation measurements is the GP-5000 GalvaPulse™ set from Germann Instruments [15] consisting of three basic elements: a measurement electrode, a silver-chlorine reference electrode and a PSION control and recording device. After appropriately connecting the apparatus to the element (Fig. 2), an electrical system is obtained, owing to which the above-mentioned electrical parameters can be measured. The results obtained from the measurements, after relating them to the reference values presented below, allow the diagnosis of reinforcement corrosion.

The reference values established for the galvanostatic pulse technique for assessing corrosion risk level of the reinforcement make it possible to determine [15]:

a) the probability of corrosion based on the stationary potential of the reinforcement at the level:
- of 5% for E_{st} > -200 mV,
- of 50% for -200 mV > E_{st} > -350 mV,
- of 95% for E_{st} < -350 mV,

b) the probability of corrosion based on the resistivity of the concrete cover as:

a) b)

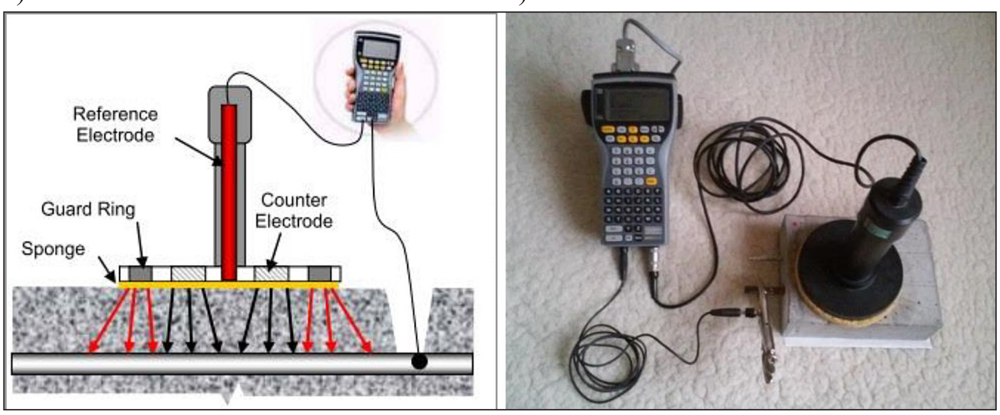

Figure 2. GP-5000 GalvaPulse™ device: (a) diagram of the device operation on the tested element [15], (b) photo of the connection of the set elements with the specimen

- low for $\Theta \geq 20$ kΩ×cm,
- medium for 10 kΩ×cm < Θ < 20 kΩ×cm,
- high for $\Theta \leq 10$ kΩ×cm,

c) the corrosion activity of the reinforcement based on the corrosion current density as:
- unpredicted for i_{cor} < 0.5 μA/cm^2,
- negligible for 0.5 μA/cm^2 < i_{cor} < 2.0 μA/cm^2,
- low for 2.0 μA/cm^2 < i_{cor} < 5.0 μA/cm^2,
- moderate for 5.0 μA/cm^2 < i_{cor} < 15.0 μA/cm^2,
- high for i_{cor} > 15.0 μA/cm^2.

The electric current generated in the GP method ranges from 5 to 400 mA, and the pulse duration is approximately 1–20 seconds. The applied direct current I_{app} at time t leads to the polarisation of the reinforcement with the potential value V_t, which can be expressed by the formula 1:

$$V_t = I_{app}\,[R_p\,[1\text{- }\exp(\text{-}t/R_p\,C_{dl}))]+R_W] \tag{1}$$

where: R_p – polarisation resistance, C_{dl} – capacity of the double layer (transition layer at the junction of concrete and steel), R_W – ohmic resistance.

In the Equation above, the polarisation resistance R_p is given by the Stern-Geary Equation (2):

$$i_{cor} = B/R_p \tag{2}$$

where: B – an empirical constant equal to 25 mV for actively corroding steel or 50 mV for passive steel, i_{cor} – the corrosion current density.

Having the above data and knowing the diameter and length of the tested section of the steel bar, it is possible to determine its corrosion activity and the increase in corrosion per unit of time.

The description above shows that the values of the measured parameters in such an unusual system as a steel rod "immersed" in wet concrete are significantly dependent on the environmental conditions under which the measurements are carried out. It has been found in research practice that the humidity of the concrete cover significantly affects the effectiveness of measurements [16, 17]. The influence of temperature has also been proven [18]. The authors' research so far has confirmed the influence of temperature on the assessment of the corrosion risk of reinforcement in concrete using the GP method. They discovered that measurements performed on the same element at different temperatures can significantly change the conclusions about corrosion prediction. Another, this time internal, factor influencing the results of parameters measured using the GP method may be the stresses occurring in the steel during testing of a loaded structure, and more specifically in the tested reinforcement bar. This may be due to the fact that the diameter and length of the tested bar are important parameters determining the corrosion current density and the polarisation resistance of the reinforcement, and they change as a result of the applied stresses. The authors of the article have not yet found any publication describing this type of research. The available literature describes only theoretical studies of the relationship between the corrosion current density and the deflection of the tested element. [19, 20]. The author of the publications describes the conclusions from the theoretical analysis regarding the relationship between the corrosion current density and the deflection of a reinforced concrete element. At the same time, the author of the publication emphasises that "The nature of the work is fully theoretical, it should be verified in a numerical approach, through process simulations, then testing of structural elements in laboratory conditions and built-in and operated elements in real working conditions". For this reason, the authors considered it justified to conduct experimental research to identify the influence of element effort on the measurement results obtained using the GP method.

EXPERIMENTAL RESEARCH

Galvanostatic pulse tests aimed at identifying expected interactions between the state of stress and corrosion activity in a reinforced concrete cross-section were performed on a reinforced concrete slab element using the GP-5000 GalvaPulse™ apparatus (Fig. 3). The tested board had dimensions of 1500×450×100 mm. The slab was made of concrete according to recipes for C20/25 class concrete. The mixture was compacted using a deep vibrator. Then, 24 hours after concreting, the slab was unmoulded and stored in the laboratory hall at a temperature of approximately ± 21 °C and humidity of approximately 50%. For a period of seven days, the slab was cared for by pouring water on it. Ribbed bars with a diameter of 8 made of BST500 steel were used as reinforcement. The cover was 20 mm. The arrangement

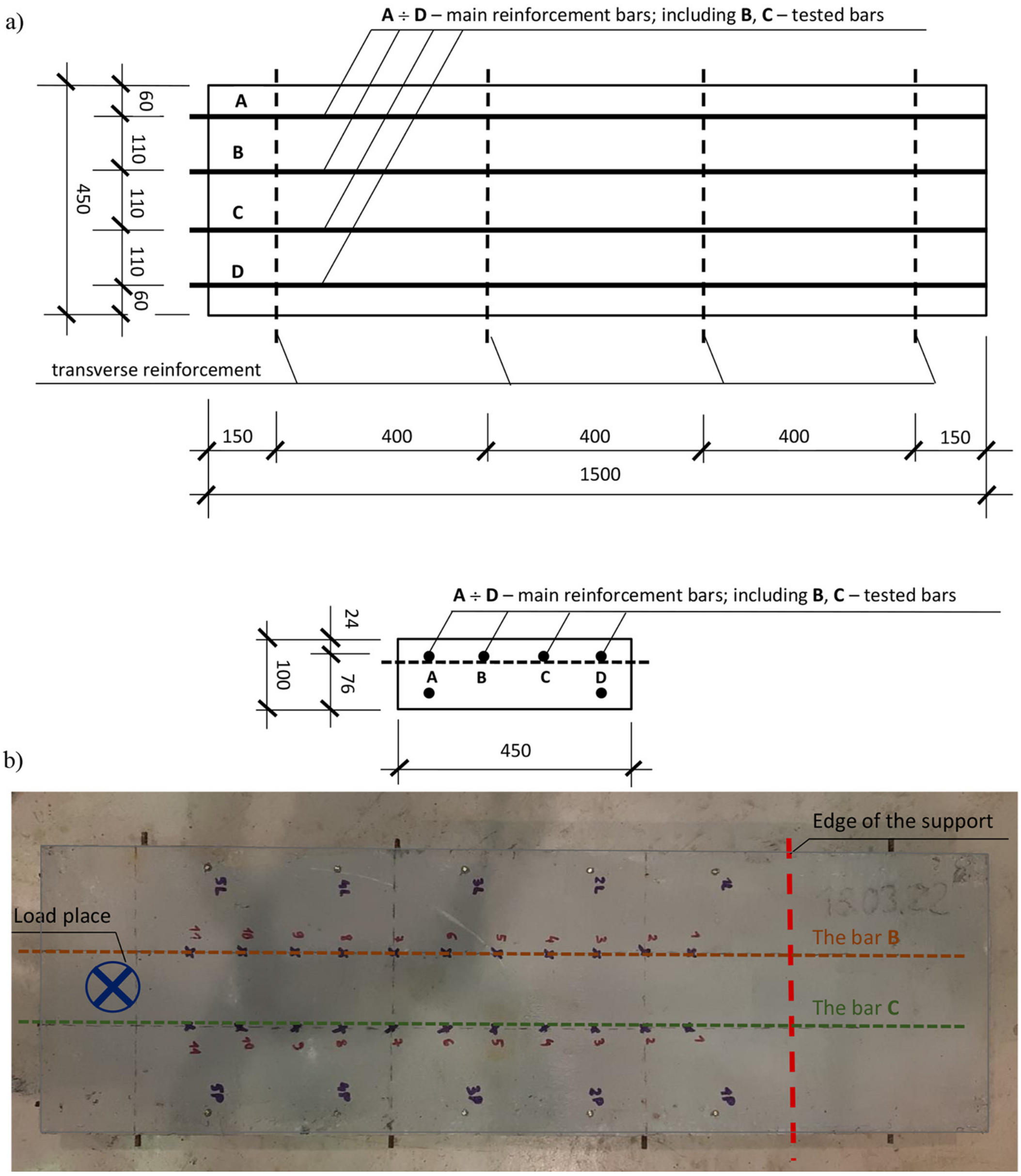

Figure 3. The tested element: (a) sketch of reinforcement arrangement, (b) marked measurement points

of the main and distribution reinforcement is shown in Figure 3a. The research program included measurements of electrochemical parameters using the GP method while loading the slab (at subsequent load levels) until its failure. A static cantilever scheme was adopted – a slab fixed at one end, loaded with one force concentrated on the unsupported other end of the slab (Fig. 4). The load was performed using a force-controlled hydraulic actuator. The slab was loaded monotonically (without unloading) in stages. Six load levels were identified before the slab failed: 0.5 kN, 1 kN, 2 kN, 4 kN, 6 kN, 8 kN, and then the slab was further loaded until failure, which occurred at a force of 9.85 kN. At each load level, with a constant set force value maintained for t = 20 minutes, measurements of electrochemical parameters were carried out. Measurements of electrochemical parameters were made for two internal bars of the main reinforcement (marked A and B) at 22 measurement points (11 points for each bar), located on the surface of the slab along the line of arrangement of a given bar, taking into account the decreasing level of stress resulting directly from the cantilever static system. The points were spaced at equal intervals of 70 mm (Fig. 3b). The obtained results for all three measured parameters are presented in the graphs in Figure 5 and Figure 6.

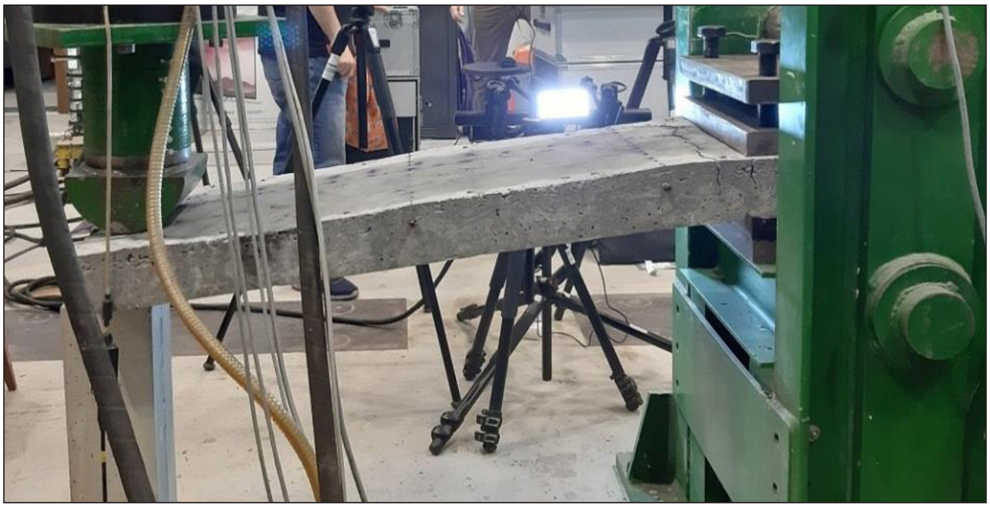

Figure 4. Damaged slab

Figure 5 presents graphs showing the change in the values of the measured parameters as a function of the slab load (F = 0.5 ÷ 9.85 kN). Each value presented is the average obtained from two measurements made at analogous points of the two tested bars. When analysing the graphs, one can observe a clear influence of the bar effort level on the obtained measurement results of electrical quantities.

The most expressive are the graphs of the value of the stationary reinforcement potential. These values clearly decrease: from the values of (-107) ÷ (-159) mV obtained at the assumed points at the first load level with force F = 0.5 kN, to the values of (-135) ÷ (-247) at the level of the maximum measured load, respectively. At the same time, it can be noticed that the largest differences in the values of the stationary potential between the measurements at the beginning and the end of the load occur in points 1 and 2 (red lines on the graph), i.e. in the points closest to the slab support – the cross-section in which the moment value was the highest and which was responsible for the destruction of the element. The smallest differences were recorded at points 10 and 11 (blue lines on the graph), located near the unsupported end of the slab.

The tendency of changes in measured values as a function of effort is also visible in measurements of corrosion current density. The values of this parameter measured at a load of F = 0.5 kN in points No. 1 and No. 2 are, respectively: 3.28 and 7.57 μA/cm^2, and at F = 9.85 kN, respectively: 6.97 and 10.58 μA/cm^2. However, the direction of changes between subsequent load levels is not as clear as in potential measurements. Fluctuations in the measured values at individual load levels in points No. 2 (red dashed line) are particularly visible (the maximum recorded value is 18.91 μA/cm^2 at a load F = 8 kN). The measurement values at this point differ significantly from all other points, probably because the main and transverse reinforcement bars intersect at this point, causing measurement distortions. The next point where the reinforcement bars intersect is point No. 7, but no anomalies were found here, which is probably due to the low effort of the slab in this cross-section.

The analysis of the results of concrete cover resistivity measurements also indicates relatively large changes in the obtained values, from the value of 2.15 ÷ 10.45 kΩ×cm (at a load F = 0.5 kN) to 1.85 ÷ 7.10 (at F = 9.85 kN), with the maximum measured value being 12.1 kΩ×cm. However, when analysing the value of this parameter, no clear trend of changes can be observed. This may be due to the fact that rheological processes in concrete last for years [2] and affect the structure of concrete, including the random formation and location of micro-defects. This issue requires further analysis.

The most visible changes in the values of the measured parameters as a function of effort were recorded at points No. 1, i.e. closest to the slab support, as shown in separate graphs in Figure 6. Dashed lines in brown and green connect the points with the values measured in bar B and bar C, respectively, while the average values from measurements in two bars are marked in red. The red lines are therefore exactly the same ones shown in Figure 5.

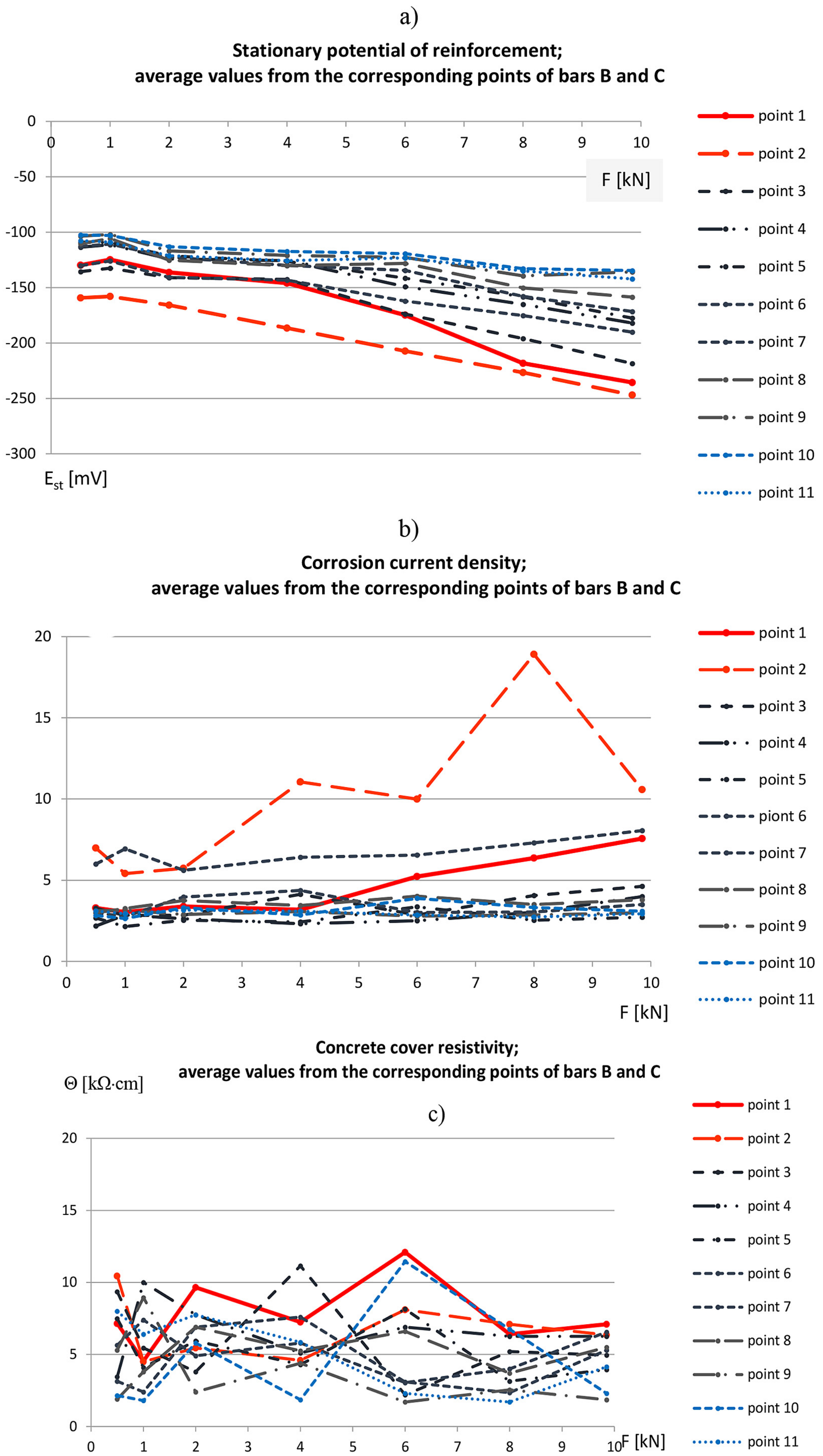

Figure 5. Average values of measured parameters as a function of load: a) reinforcement stationary potential, (b) corrosion current density, (c) concrete cover resistivity

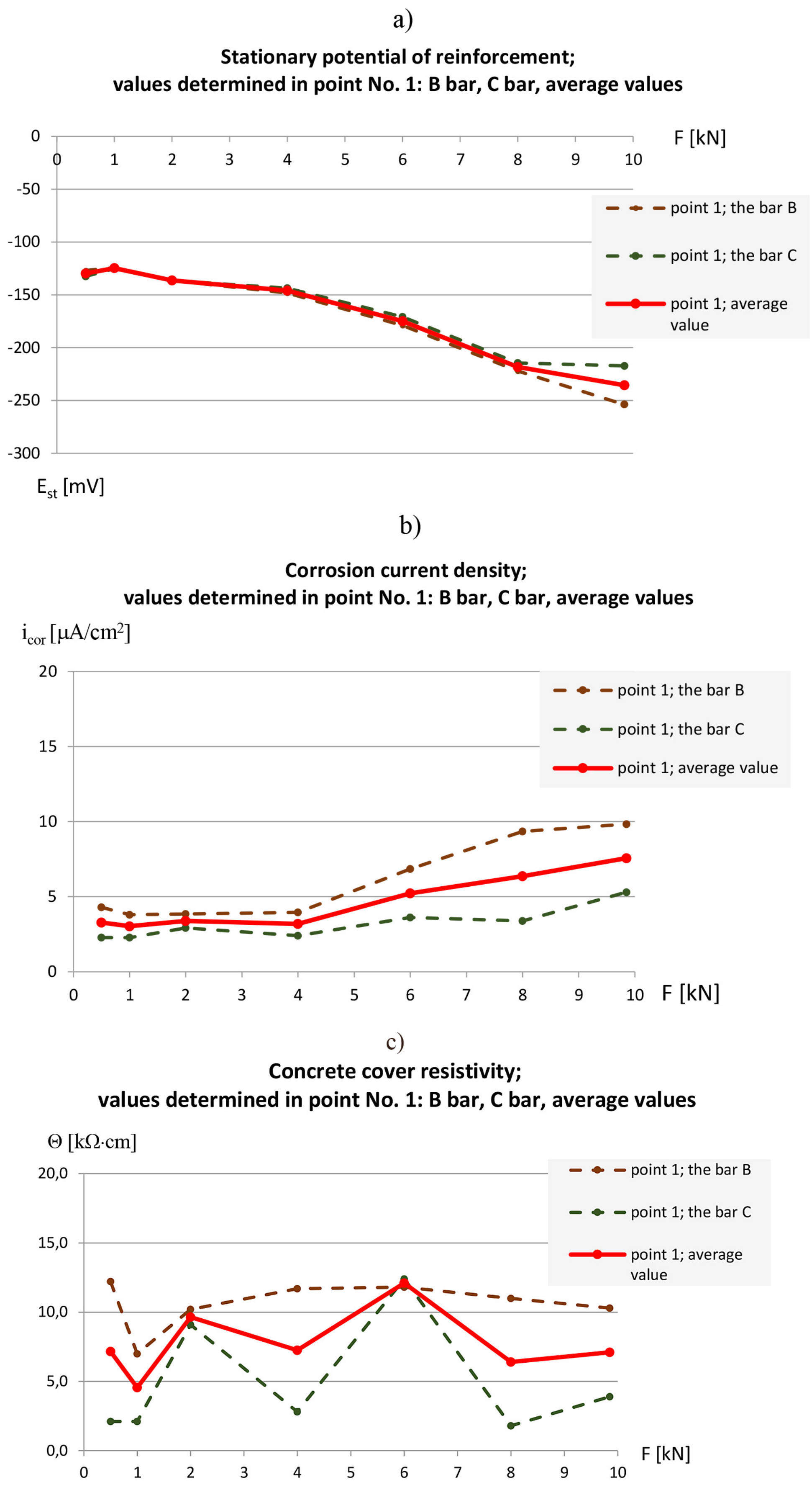

Figure 6. Values obtained for point No. 1 – where the slab is supported: a) reinforcement stationary potential, b) corrosion current density, c) concrete cover resistivity

CONCLUSIONS

The research conducted and described in the article allowed demonstrating a clear influence of the effort of the reinforced concrete element on the values of three parameters measured to assess the degree of corrosion of the reinforcement in concrete using the galvanostatic pulse method.

This influence is most clearly visible in the measurements of the stationary potential of the reinforcement at the points located closest to the support (points No. 1) due to the greatest effort in the slab cross-section. At the analysed points, the average difference between the potential values measured at the minimum load ($F_{\min}$) and the maximum load (F_{max}) was 105.91 mV, which is 82% referring to the value obtained with F_{min}. Such different values also fundamentally change the conclusions about the probability of corrosion occurrence, from 5% (at minimum effort) to 50% (at maximum effort), according to the criteria given in [15]. Assuming an operating strain of approximately 0.5 of the maximum strain, one can expect an E_{st} value of approximately (-175) mV (which in this case does not change the conclusions about the probability of corrosion).

The analysis carried out in a similar way for the corrosion current density shows a difference of 4.92 μA/cm^2 (from 3.27 to 7.57) which is as much as 131% in relation to the value measured at the minimum load (F_{min}). At the same time, this changes the conclusion about the corrosion activity of the reinforcement from negligible to moderate, which means a jump by two levels according to the criteria given in [15]. For operational load, it may be approximately 4.75 μA/cm^2 and indicate the corrosion activity of the reinforcement at the border between low and moderate (according to [15]). The average resistivity values of the concrete cover do not allow for capturing a clear trend of changes as a function of effort. However, it can be said that they are varied and the extreme difference between the measured values (minimum: 4.55 kΩ×cm, and maximum: 12.1 kΩ×cm) is 7.55 kΩ×cm, which is 166% with respect to the value measured at the minimum load (F_{min}).

The research above shows that in practice, when using the galvanostatic pulse method to predict the corrosion of reinforced concrete structure elements, the obtained measurements should always be analysed in relation to the location of the measurement points and the element effort at the considered points. Correction factors developed for measurements performed with this method in various states of element stress could be helpful. Currently, the authors of the publication are conducting research in this area.

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