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Effect of cover thickness on reinforcement corrosion in large plate elements exploited in two different exposure classes – A case study

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ABSTRACT

In reinforced concrete structures, a key influence on the protection of reinforcement against corrosion is the properly designed and constructed concrete cover, the thickness of which should be adopted according to the exposure class in which the structure will be used. This article presents the standard guidelines for the design of concrete cover and the changes that have been made in this area in successive standards with a noticeable trend toward increasingly stringent regulations. Also summarised are the results of tests performed for two elements of the structure of a residential building (made with W-70/MK large slab technology) designed for two different exposure classes, ie, the exterior wall of the loggia and the interior wall of the kitchen, in which improperly executed concrete cover led to the development of corrosion of the reinforcement. The tests were carried out using nondestructive methods using PS 200 ferroscan to determine the distribution of the bar and the thickness of the cover, and the galvanostatic pulse method to assess the corrosion of the reinforcement.

Keywords: concrete cover, corrosion, reinforcement, exposure class, non-destructive methods.

INTRODUCTION

When designing buildings, it is necessary to ensure that they have an adequate level of reliability [1, 2, 3], which according to EN 1990 [4] is defined as the 'ability of a structure or a structural member to meet the specified requirements, including the working life, for which it has been designed'. Additionally, in terms of the aforementioned standard, this concept includes issues related to ensuring ultimate limit states (ULS), serviceability (SLS – service limit state), and durability. Correctly designed civil structures, meeting the relevant design assumptions in effect at the time of the project's inception, should ensure their failure-free use without significant repairs for the entire design period, despite the impact of various external factors, both related to operation and the negative influence of environmental conditions. It should be added that the assurance of reliability is due not only to the proper design of the structure, but also to its correct execution, as well as its subsequent use with periodic inspections.

In the case of reinforced concrete structures, ensuring reliability in the design stage involves both properly determining the load bearing capacity and stability of the elements by determining the appropriate dimensions of the sections, the amount and distribution of reinforcement, and ensuring durability by adopting the appropriate cover of reinforcing bars [5] to protect them against corrosion [6] and in case of fire [7]. The concrete cover should be designed according to standard guidelines [8], which define its parameters (including, above all, thickness) adequately for the exposure class of the structure, i.e. the conditions under which the structure will be used, as well as the fire resistance class of the building and the elements of the fire resistance of the building [9], i.e., in case of fire action. The standard [8] (as well as previous regulations) specifies the concept of concrete cover thickness, understood as the minimum distance from the outer surface of the concrete to the nearest reinforcement regardless of whether it is the main longitudinal, transverse, or secondary reinforcement, or even the installation reinforcement, because as a result of improper covering, even secondary reinforcement can be corroded, resulting in detachment of a layer of concrete, thus significantly reducing the original concrete cover thickness of the main reinforcement and reducing the working life of the entire element.

In addition to the proper design of the cover in the reinforced concrete structural elements, its execution is also of great importance [10]. This applies to both monolithic structures, made on site, and pre-fabricated structural elements created in pre-fabrication plants [9]. It is assumed that a greater danger of deviations from design assumptions may occur when elements are manufactured on site than in manufacturing plants. Therefore, in various types of guidelines, one can find provisions for adopting larger concrete cover thickness inventories for monolithic construction elements than for prefabricated ones. This is an approach that is correct in theory, since in closed manufacturing plants, characterised by a certain repetition of production and greater supervision, there is less risk of errors than in the case of a standard construction process.

This assumption, among others, guided the designers and builders of large panel buildings, who created structural elements in the so-called ‘house factories’ [11]. However, such an approach is not entirely safe, since during the manufacture of pre-fabricated elements, execution errors and inadequate quality control of production can also occur, as indicated by the results of pre-fabricated structural element measurements [9, 12, 13]. For obvious reasons, this affects the reliability and durability of building structures [14]. Currently, this problem is quite serious, because current trends in the development in Poland do not indicate that in the coming years there will be a sudden supply of new housing and the eventual replacement of old large-panel settlements with new residential buildings [15]. The opposite phenomenon is noticeable; as a result of the cost of new housing, the useful working life of large-panel buildings will be extended. Therefore, it is necessary to monitor their condition [16, 17] and conduct research on their further safe use, as well as planning the scope of repairs [18, 19] so that useful working life can be optimally increased. At the same time, more attention should be paid to the production of pre-fabricated elements, as workmanship errors still occur [9].

STANDARD GUIDELINES FOR COVER IN REINFORCED CONCRETE ELEMENTS

Guidelines for determining the necessary (minimum) thickness of the reinforcing bar cover in reinforced concrete elements can be found in all subsequent versions of the standard for the design of concrete structures, although new modified provisions usually appear with subsequent revisions.

PN-B-03264:1984 standard [20]

According to the provisions of the standard [20], the concrete cover of the reinforcement should be not less than:

- maximum diameter of covered reinforcement,
- 10 mm ‘in slabs, thin-walled structures, dense ribbed ceilings and walls up to 100 mm thick’,
- 20 mm for main reinforcement and 10 mm for stirrups and assembly reinforcement in walls > 100 m, beams and columns.

At the same time, it was noted that the concrete cover must not be less than that prescribed by fire regulations.It also indicated the cases for which the thickness of the cover should be additionally increased by:

- 5 mm when there is a direct impact of atmospheric influences,
- 5 mm when the element is located in nonhydrated soil,
- 5 mm when the element is located in a room with relative humidity > 70%,
- 10 mm when the element is constantly in contact with water.

In addition, it is possible to reduce the thickness of the cover by 5 mm in the precast and vibrated element, with a minimum concrete class B15 (C12/15) (concrete class designation, B according to Polish standards, C according to the European standards, 15 means the strength of 15 MPa measured in cubic samples 15 × 15 × 15 cm) (according to the designations in force at the time) with a minimum cover of 10 mm and maintaining the required fire resistance.

It was also noted that if lean concrete with a minimum thickness of 10 cm under the foundation was used, the cover of the reinforcement should be at a level of min. 50 mm, and for the bottom reinforcement 70 mm.

These requirements refer to the classes of aggressive environments contained in the PN-80 / B-01800 standard [21], with a division into solid, liquid, or gaseous environments (and an additional division of each).

PN-B-03264:1999 standard [22]

In the 1999 standard [22], there was a provision that the cover should ensure the adhesion of the steel to the concrete and protect the steel itself from corrosion and fire. Accordingly, the cover should be no less than:
- the maximum diameter of the covered reinforcement or bundle of bars,
- maximum aggregate grain size increased by 5 mm.

Furthermore, the cover was related to environmental conditions, thus defining its minimum thickness determined on the basis of seven environmental classes, while also determining the maximum w/c (water to cement ratio) ratio and the minimum cement content. Situations are also indicated in which the minimum thickness of the concrete cover can be reduced by 5 mm.
- in slab elements,
- in elements made of concrete of a class greater than or equal to B50 (concrete class designation, B according to the Polish standards, C according to the European standards, 50 means strength of 50 MPa measured on cubic samples 15 × 15 × 15 cm).

At the same time, the cover after reduction should not be less than that required for Class 1 environment, that is, dry environment (i.e. conditions in the interior of residential buildings, offices, and industrial halls).

It was also pointed out that for foundations, when lean concrete is poured under them, the reinforcement cover can be used at a minimum of. 40 mm, and for elements laid directly on the ground, not less than 75 mm.

Furthermore, the dimensional deviations of the cover thickness Δh (dimensional deviations of the cover thickness [L22]) were successively adopted:
- up to 5 mm for prefabricated elements,
- from 5 to 10 mm for elements made on site.

PN-B-03264:2002 standard [23]

The 2002 standard [23] gives revised provisions for reinforcement cover based largely on those of the standard [22], and the differences that occur include the following.
- additional dependence of the minimum thickness of the cover on the aggregate grain size exceeding 32 mm; in this situation, the cover thickness should be increased by 5 mm;
- taking into account the change in the classification and assumptions of exposure classes and their impact on the correction of the minimum cover thickness, the maximum w/c ratio, and the minimum cement content in the mix.

Since the standard design period based on which the cover parameters were determined is 50 years, it was additionally determined that for a design period of 100 years, the cover should be increased by 10 mm and the intermediate values should be interpolated. Furthermore, for elements with exposed aggregate or uneven surface, the thickness of the cover should be increased by 5 mm.

Cases for which the minimum thickness of the cover can be reduced are also indicated:
- if a concrete class higher than the recommended one is used, provided the exposure class is other than XC1 (exposure class with carbonation-induced corrosion for elements dry or permanently wet [L8] [L23], [L25]),
- reinforcement is made of stainless steel,
- other protection of steel or concrete against corrosion of reinforcement was used,
- concrete with a special composition was used.

The same version as in the 1999 standard [22] left recommendations for cover in foundations and deviations used. However, separate attention was paid to particularly aggressive environments, XF (exposure class with freez/thaw attack [L8] [L23], [L25]) and XA (exposure class with chemical attack [L8] [L23], [L25]), for which the need to control the structure of the concrete and the use of special layers of surface protection was recommended. Above that, the paper [24] points out the differences from the 1984 regulations.

PN-EN 1992-1-1:2008 standard [8]

Current standard regulations assume that the appropriate covering of the reinforcement with concrete depends on basic factors such as the class of construction, the class of concrete, and

the environmental conditions (determined by the exposure class). Hereby, the minimum reinforcement cover (c_{min}), that is, the smallest distance between the surfaces of the concrete and the bar, was precisely defined as a value not less than:
- maximum diameter of the reinforcement ($c_{min,b}$),
- the minimum cover due to environmental conditions and the class of construction ($c_{min,dur}$);
- 10 mm.

Furthermore, the cover should be increased by a deviation Δc_{dev} (deviation of the reinforcement cover [L8] [L23], [L28]) from the recommended value of 10 mm according to the national annexe. It is possible to modify this value in the range of 5 × 10 mm for elements for which a quality assurance system is applied during execution and the cover is subject to special inspection. It is even possible to use values of 0 × 10 mm if the measuring apparatus used is very sensitive, and components that do not meet the requirements will be rejected.

On the other hand, the use of appropriate protection, including corrosion resistant materials or concrete of a higher class than recommended, makes it possible to reduce the required cover thickness (c_{nom}).

It was also indicated that the concrete cover calculated from the contact surface can be reduced in both on-site and pre-fabricated elements, provided that:
- a concrete class of not less than C25/30 (concrete class designation, according to the European standards, 30 means strength of 50 MPa measured on cubic samples 15 × 15 × 15 cm, 25 means strength of 25 MPa measured on cylindrical samples 15 × 30 cm) is used;
- the time of exposure of the rooms to the external environment is less than 28 days,
- a rough contact surface is used.

Furthermore, in the case of aggressive classes XF and XA, as in the standard [23], attention should be paid to the composition of the concrete taking into account the provisions of PN-EN-206 [25].

A detailed description of aggressive environments is included in PN-EN 206 [25], which introduced the grouping of environmental impacts into 18 exposure classes (in the national supplement - PN-B-06265:2004 [26] there are an additional 3 exposure classes XM – exposure class with erosion attack [L8] [L23], [L25]), according to which the reinforcement cover should be designed.

When designing the covers, it is also necessary to follow the requirements of EC2-part 2 [27] taking into account the design for fire conditions.

PrEN 1992-1-1 standard, ver. 2021-01 [28]

Several changes will be found in the next version of the European standard, prEN 1992-1-1 [28] for the revision of the covers for concrete reinforcement. These are related to, among other things:
- extension of the classification of exposure classes, where, in addition to the division into classes itself, classes of resistance to a given ERC (Exposure Resistance Class [L28]) exposure were additionally introduced, mainly related to XRC (Exposure class (carbonation) [L28]) carbonisation, XRSD (Exposure class (chlorides) [L28]), and XRF (Exposure class (freeze/thaw attack) [L28]) freeze-thaw damages;
- changing the selection of minimum cover for durability ($c_{min,dur}$) based on ERC and exposure classes, according to the tables in the standard [28],
- increasing the thickness of the cover depending on the direction of soil interaction; by 5 mm for soil pushing from the side of the foundation and 0 mm for soil under the foundation;
- decreasing the thickness of the cover by 5 mm for buildings designed for a period of 30 years, for which the cover was adopted as for structures designed for 50 years;
- reducing the thickness of the cover by 5 mm for elements, the execution of which takes into account special control processes concerning, among other things, geometry or care,
- reducing the thickness of the cover by 10 mm for elements that are additionally protected with special coatings,
- indications on the use of performance deviations and when they should be used.

However, the procedure itself to estimate the thickness of the cover (in addition to the above changes) is analogous to PN-EN-1992-1-1 [8].

INFLUENCE OF COVER THICKNESS ON DAMAGE TO REINFORCED CONCRETE ELEMENTS OF LARGE PANEL SYSTEM BUILDINGS

Analyzing the cover thickness of elements in large-panel structures made in the 1990s, which are currently in the middle of their useful life, it can be concluded that in many cases the cover of the reinforcement was made not in accordance with the standard regulations in force at that time.

Therefore, it also does not meet current standards. As a result, numerous damage and corrosion can be observed in the reinforcement in many structures. This is especially visible in external elements exposed to the negative impact of atmospheric factors (Fig. 1).

This problem was also presented in [29], which described the case of a balcony loggia wall in a building built in the 1990s using the W-70 / MK large-panel technology. The tests carried out at that time, including the scanning method using the PS 200 ferroscan (Fig. 2a) and the polarised galvanostatic pulse method using the GP-5000 GalvaPulse™ apparatus (Fig. 2b) to estimate reinforcement corrosion, showed workmanship errors, insufficient reinforcement cover and the occurring corrosion foci in parts of the wall, as shown by the sketches in Figure 3 and the results obtained from the study (Fig. 4).

The sketches illustrate the actual layout of the reinforcement (black lines) obtained by scanning the wall surface with a Hilti PS 200 ferroscan, on which colour maps of the distribution of parameter values were plotted to determine the probability of the existence of corrosion in these areas and to assess the corrosion activity of the tested bars obtained by the GalvaPulse method. The measured parameters were the stationary potential of the reinforcement (Fig. 3a) and the resistivity of the concrete cover (Fig. 3c), which provide information on the probability of corrosion, and the corrosion current density (Fig. 3b), from which the corrosion activity of the reinforcement can be estimated. Based on the tests and analyses carried out (described in detail in [29]), it was determined that the thickness of the cover on the diagnosed wall varied, depending on where it was measured, from 5 to 10 mm, while the standard requirements were 20 mm according to the standard [20] and even 25 mm according to the standard currently in force [8]. However, the probability of corrosion determined by the values of the stationary potential of

a) b) c)

Figure 1. Damage images in structural elements of large-panel blocks: a) column at the entrance to the building, b) reinforced concrete bracket at the loggias, and c) column supporting the balcony

a) b)

Figure 2. a) Ferroscan Hilti PS 200 b) GalvaPulse™

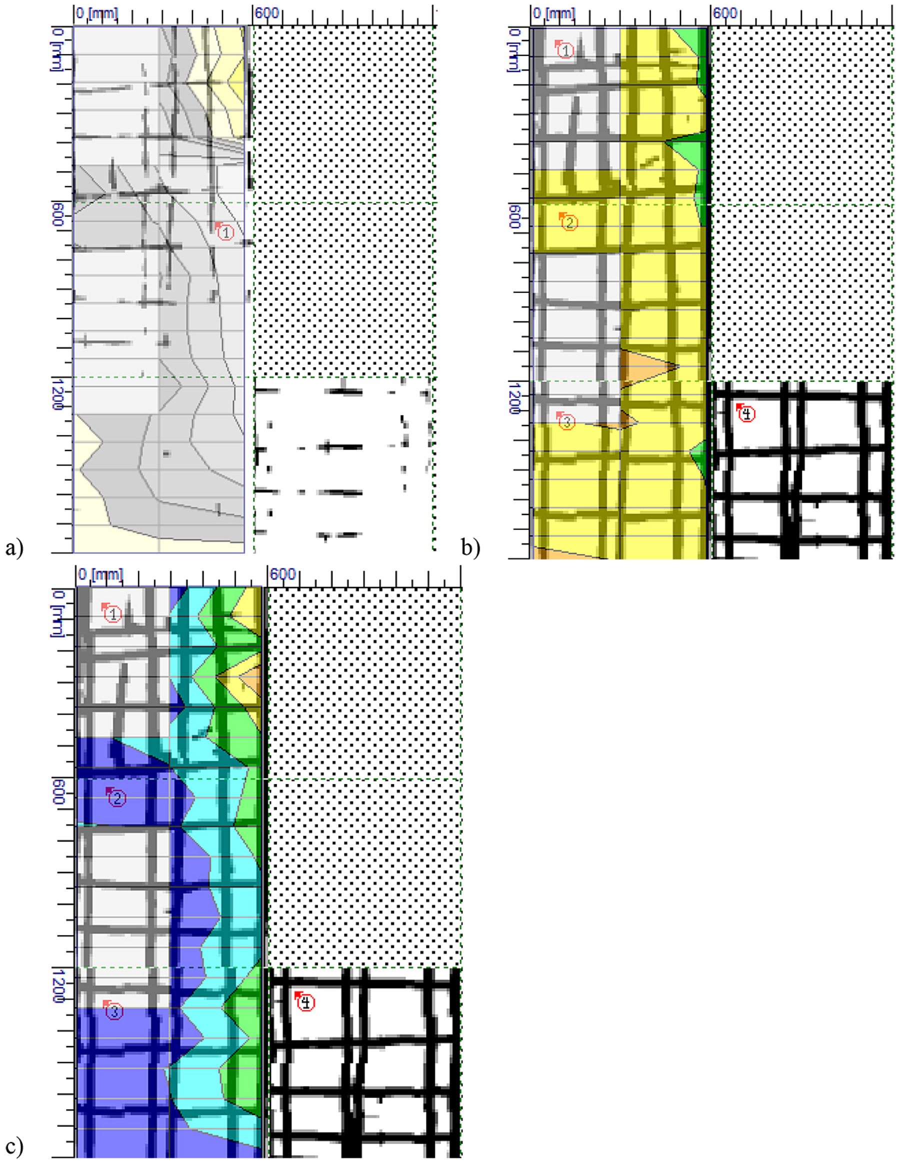
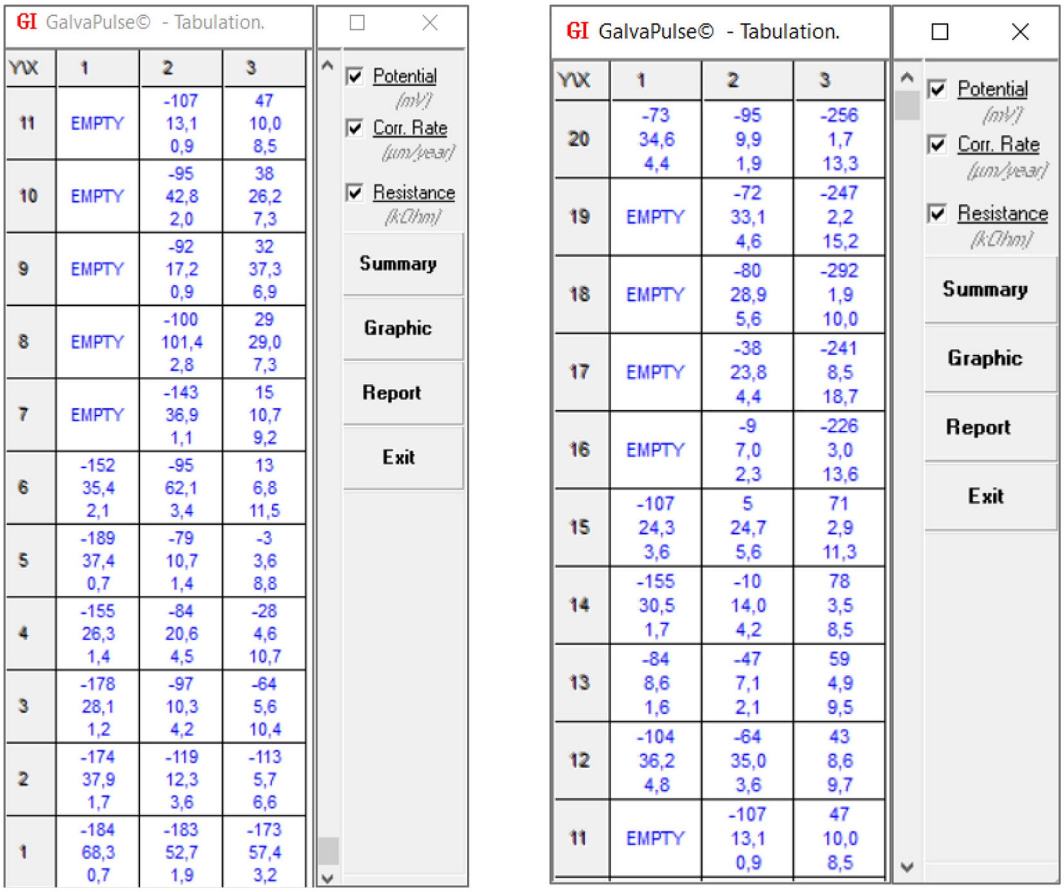


Figure 3. Images of the logia wall reinforcement system with applied colour corrosion estimation maps and a table of results obtained by the GalvaPulse™ method: a) stationary potential of reinforcement, b) corrosion current density, c) resistivity of the concrete cover [29]

the reinforcement and the resistivity of the concrete cover determined in the regions of the smallest thickness of the cover was estimated at 50% and determined as medium or high, and the corrosion activity of the reinforcement as moderate (according to the criteria in Section 4 of this article), which for a 30-year-old building is quite alarming.

These studies and analyses show that due to manufacturing errors related to the failure to maintain the correct thickness of the cover during the production of prefabricated reinforced concrete elements, there is a high risk of reinforcement corrosion in the elements of large-panel buildings. The most vulnerable appear to be external elements, such as the aforementioned loggia wall, but also the walls of the facade, balcony slabs, or load-bearing columns, which are exposed to direct atmospheric conditions. Currently, this problem is partially solved with thermomodernisation of buildings (resulting from the desire to reduce CO_2 and achieve savings in heating - energy certificates), whereby additional layers of insulation separate facade walls from external environmental influences and reduce the risk of corrosion. However, this problem still affects elements that are not subject to thermomodernisation, such as flaccid exterior columns, which in the long term can reduce their load-bearing capacity and reduce the safety of the entire structure (Fig. 1c, Fig. 5).



GalvaPulse© - Tabulation.

Y\X	1	2	3
11	EMPTY	-107 13,1 0,9	47 10,0 8,5
10	EMPTY	-95 42,8 2,0	38 26,2 7,3
9	EMPTY	-92 17,2 0,9	32 37,3 6,9
8	EMPTY	-100 101,4 2,8	29 29,0 7,3
7	EMPTY	-143 36,9 1,1	15 10,7 9,2
6	-152 35,4 2,1	-95 62,1 3,4	13 6,8 11,5
5	-189 37,4 0,7	-79 10,7 1,4	-3 3,6 8,8
4	-155 26,3 1,4	-84 20,6 4,5	-28 4,6 10,7
3	-178 28,1 1,2	-97 10,3 4,2	-64 5,6 10,4
2	-174 37,9 1,7	-119 12,3 3,6	-113 5,7 6,6
1	-184 68,3 0,7	-183 52,7 1,9	-173 57,4 3,2

Potential (mV)
Corr. Rate (µm/year)
Resistance (kOhm)
Summary
Graphic
Report
Exit

a)

GalvaPulse© - Tabulation.

Y\X	1	2	3
20	-73 34,6 4,4	-95 9,9 1,9	-256 1,7 13,3
19	EMPTY	-72 33,1 4,6	-247 2,2 15,2
18	EMPTY	-80 28,9 5,6	-292 1,9 10,0
17	EMPTY	-38 23,8 4,4	-241 8,5 18,7
16	EMPTY	-9 7,0 2,3	-226 3,0 13,6
15	-107 24,3 3,6	5 24,7 5,6	71 2,9 11,3
14	-155 30,5 1,7	-10 14,0 4,2	78 3,5 8,5
13	-84 8,6 1,6	-47 7,1 2,1	59 4,9 9,5
12	-104 36,2 4,8	-64 35,0 3,6	43 8,6 9,7
11	EMPTY	-107 13,1 0,9	47 10,0 8,5

Potential (mV)
Corr. Rate (µm/year)
Resistance (kOhm)
Summary
Graphic
Report
Exit

b)

Figure 4. Table of results obtained by the GalvaPulse™ method [29]

When analysing the quality of the cover in prefabricated elements of residential buildings, the structural elements located inside the buildings cannot be ignored either. This is due to the fact that some elements of the internal structure are exposed to negative environmental influences. This especially applies to rooms such as kitchens and bathrooms, where due to their functions, there are problems with gravity ventilation and increased humidity. In the walls or ceilings of such rooms, an inadequately constructed concrete cover, too small, may not protect the reinforcement against corrosion. A similar problem may also occur in other rooms with poor air circulation and too weak ventilation, which has been happening more and more frequently due to too tight windows. In conclusion, when modernising large slab buildings, in addition to thermal modernisation, the scope of necessary repairs and renovations should be thoroughly analysed. In this case, the evaluation of the condition of the concrete cover and the reinforcement of the structural elements are crucial. Therefore, repairs should include not only the return to the state before damage, but also adaptation of the element to current standards. This is particularly important in the case of loggias and balconies, which are generally not modernised and, due to their location, have a greater tendency for damage to occur as a result of the external environment contributing to a reduction in the durability of the object.

This article presents research results on the assessment of the corrosion hazard of pre-fabricated element reinforcement in large slab structures in the context of the location of the reinforcement and the influence of environmental conditions on the applied thickness of the cover in these elements.

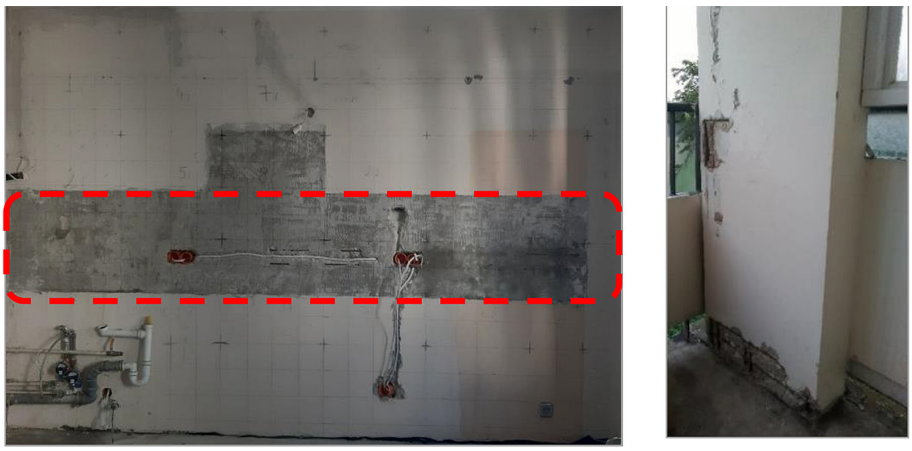
RESEARCH CONDUCTED

This article focusses on the study of a prefabricated reinforced concrete shield that is a load-bearing wall that separates the kitchen room and the stairwell in one of the apartments of a building constructed in the 1990s using the W-70/MK system (Fig. 6a). The study was carried out on the

Figure 5. Flaccid columns supporting balconies in a buildings erected in large panel system

occasion of a renovation being carried out in the apartment. Adjacent to the load-bearing wall to be diagnosed were elements of the water and gas system, along with the relevant appliances: sink, stove, oven, which were removed for the renovation. The results obtained from the examination of the interior wall were also analysed in relation to the loggia wall located in the same apartment, described in [29] (Fig. 6b).

Due to the agreement with the building manager, only non-destructive testing could be performed. Therefore, the research used a scanning method to determine the position and parameters of the reinforcement and an electrochemical method for assessing reinforcement corrosion. The research was carried out in two stages. In the first, a Hilti-branded reinforcement scanner, the Ferroscan PS 200, was used. This device allows detection and localisation of steel elements in the structure, mainly reinforcement in reinforced concrete structures. It enables the determination of the spacing of reinforcement and its cover, with the scanning



a) interior wall b) loggia wall[29]

Figure 6. Photos of the tested large plate elements

parameters declared by the manufacturer, the most important of which are:

- position of the bar axis with an accuracy of ± 3 mm,
- maximum diameter of the bar,
- The maximum depth of localisation and determination of the rod is 60 mm (accuracy ± 1 mm)
- maximum measuring depth up to approx. 18–20 cm,
- measuring range of covers from 10 mm to about 100 mm (± 10% of measured depth),

Based on the measurements, the general distribution of the reinforcement was determined, along with an estimate of the thickness of the coverings, with the main focus on indicating the places where the thickness of the coverings is the smallest, especially in the area where the analysis of reinforcement corrosion was carried out.

According to the above, the corrosion hazard status of the selected reinforcement bars was also evaluated in the elements tested using the electrochemical polarisation galvanostatic pulse method [31]. The device used for the measurements was GP-5000 GalvaPulse™, which allows simultaneous measurement of three parameters: stationary reinforcement potential (E_{st}), resistivity of concrete cover (Θ) and corrosion current density (i_{cor}). The results obtained from the measurements were related to the corresponding reference values, which made it possible to determine the following.

a) probability of corrosion based on the stationary reinforcement potential at:

- 5% at E_{st} > -200 mV,
- 50% at -200 mV > E_{st} > -350 mV,
- 95% at E_{st} < -350 mV;

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

- small at Θ
- ≥ 20 kΩ×cm,
- medium at 10 kΩ×cm < Θ < 20 kΩ×cm,
- large at $\Theta \leq$ 10 kΩ×cm;

c) corrosion activity of reinforcement based on corrosion current density as:

- non-prognostic at i_{kor} < 0.5 μA/cm^2,
- non-significant at 0.5 μA/cm^2 < i_{cor} < 2.0 μA/cm^2,
- low at 2.0 μA/cm^2 < i_{cor} < 5.0 μA/cm^2,
- moderate at 5.0 μA/cm^2 < i_{cor} < 15.0 μA/cm^2,
- high at i_{cor} > 15.0 μA/cm^2.

On the wall that constitutes an internal element of the building structure, after removing the plaster layer and cleaning the exposed wall surface, the reinforcement placement was scanned with the Hliti PS 200 ferroscan. Based on images of reinforcement scans and small discolourations visible on the concrete surface at a height of approximately 1.0 m from the floor level, indicating the presence of rust, an area was separated for testing including two horizontal parallel reinforcement bars (Fig. 7), for which the galvanostatic pulse method determined the probability of corrosion occurrence and the corrosion activity of each rod was estimated. In the tested area, eight measurement points were established for each of the two rods, placed on the concrete surface along the line of each rod at equal intervals of 15 cm. In total, 16 measurement points were determined, marked according to the adopted coordinate system from (1.1) to (8.2), but measurements could not be performed.

As already mentioned, due to arrangements with the building manager, it was not possible to perform destructive tests, nor could samples be taken for laboratory tests. Therefore, no material tests were performed and it was impossible to perform fracture surface topography analysis (FRASTA) [32] or Entire fracture surface topography [33]. Such research could allow for the identification of the mechanism of crack formation.

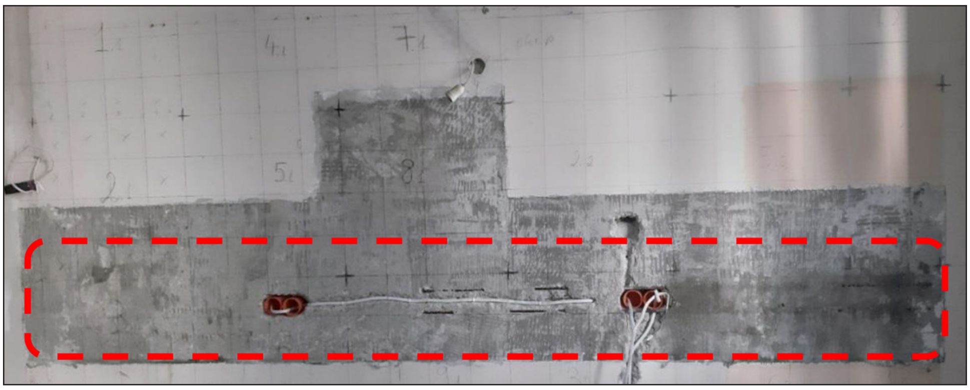


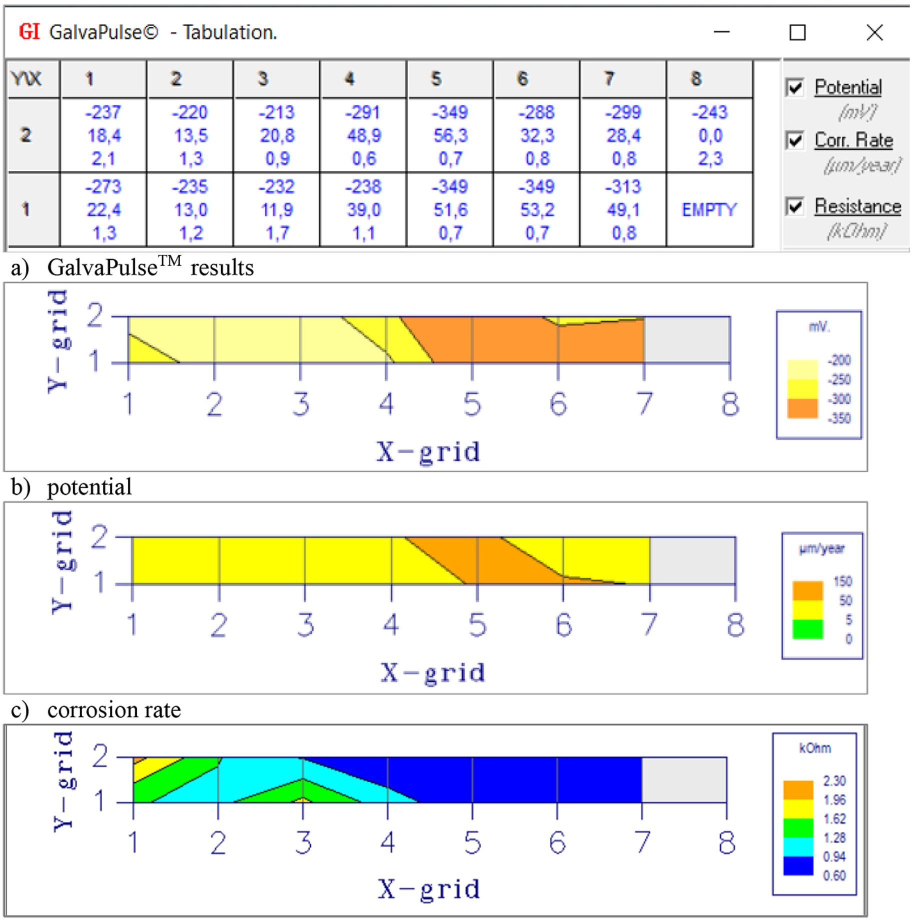
Figure 7. Photo of a wall section under test

ANALYSIS OF OBTAINED TEST RESULTS

The results of the measurements of the three parameters made by the galvanostatic pulse method for the inner wall (Fig. 8), as well as for the loggia wall studied earlier (Figures 3 and 4), were summarised in separate tables generated in the GalvaPulse™ programme, along with graphical maps of the distribution of their values, with corrosion rate values in [µm/year] given in the tables instead of the corrosion current density.

Analysis of the results obtained for the inner wall showed that for both bars the stationary potential of the reinforcement were similar, being in the range of E_{st} = (-213 ÷ -349) mV, indicating a 50% probability of corrosion. The results of the corrosion current density analysed simultaneously for both precasts indicated that at 6 measurement points the current density did not exceed i_{cor} = 2µA·cm^{-2} reaching from 1.03 to 1.93), indicating insignificant corrosion activity of the reinforcement, while the remaining 11 points recorded values in the range of i_{cor} = (2.45 ÷ 4.86) µA·cm^{-2}, which allows to conclude that the corrosion activity of the reinforcement is low and the corrosion rate is a maximum of 56.3 µm·year^{1}, provided that the environmental conditions do not change. At the same time, the highest corrosion activity of the reinforcement was recorded at the points with coordinates x = 5 and x = 6, i.e., about i_{cor} = 4.59 ÷ 4.86 µA·cm^{-2}. The resistivity of the concrete cover at all the measurement points for both bars had values lower than Θ = 10 kΩ·cm (0.6 ÷ 2.3), which suggests a high probability of corrosion. In this case, the study of this parameter may be partially contaminated by the high moisture content of the concrete at the time of measurement, which may have affected the results (Figure 9).

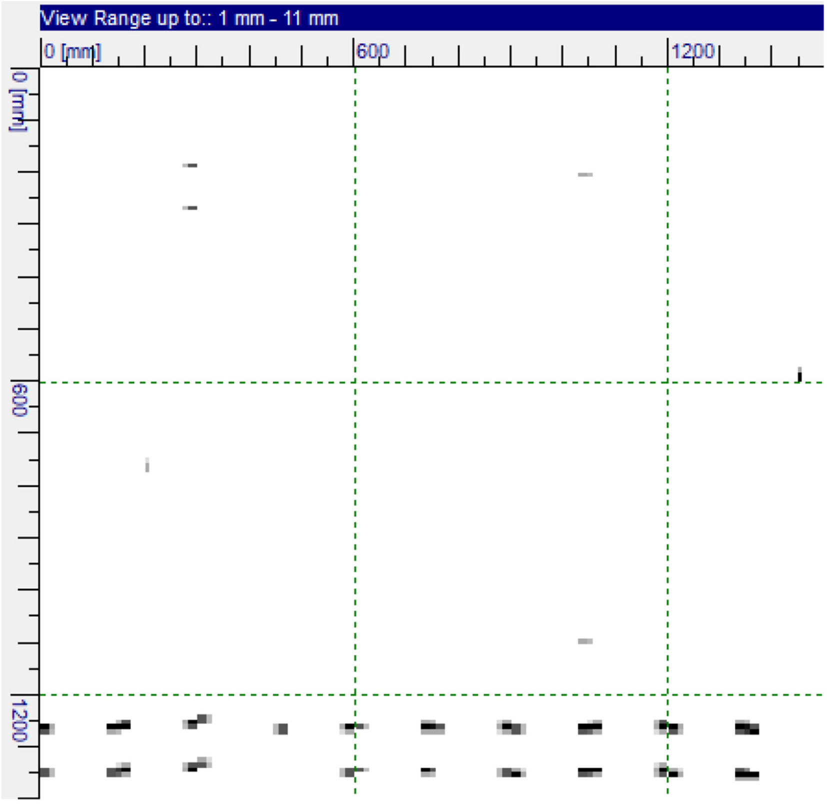
The observation of maps that show the distribution of the stationary potential of the density of the reinforcement, the corrosion current and the resistivity of the concrete cover, together with the image derived from the scans of the reinforcement system and the estimated thickness of the concrete cover, clearly indicates that the highest probability of corrosion (E_{st} < -250 mV oraz Θ = 0.6 ÷ 0.8 kΩ·cm), as well as the highest



Y\X	1	2	3	4	5	6	7	8
2	-237 18,4 2,1	-220 13,5 1,3	-213 20,8 0,9	-291 48,9 0,6	-349 56,3 0,7	-288 32,3 0,8	-299 28,4 0,8	-243 0,0 2,3
1	-273 22,4 1,3	-235 13,0 1,2	-232 11,9 1,7	-238 39,0 1,1	-349 51,6 0,7	-349 53,2 0,7	-313 49,1 0,8	EMPTY

Figure 8. Results of the parameters measured by the GalvaPulse™ method: a)tabular summary, b) stationary potential of the reinforcement, c) corrosion current density, d) resistivity of the concrete cover

corrosion activity of the reinforcement (i_{cor} = 4.59 ÷ 4.86 μA·cm^{-2}) were registered at points where the thickness of the cover ranged from approximately 3 to 15 mm, which significantly deviated from the minimum required. However, a comparative analysis of the results obtained from galvanostatic pulse measurements made for the exterior wall of the loggia and the interior wall of the apartment indicates that environmental conditions, including atmospheric factors, have a decisive

a)


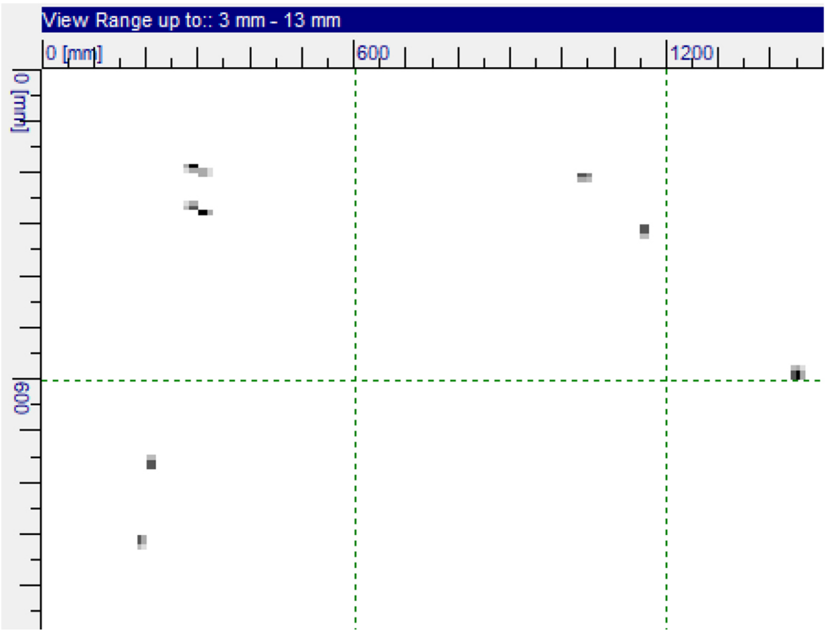


Figure 9. Images of the reinforcement system and the cover thickness on the analysed wall with colour-coded maps of corrosion estimation by the GalvaPulse^{TM} method a) image of the reinforcement at a depth of 1–11 mm, b) image of the reinforcement to a depth of 3–13 mm), c) image of the reinforcement at a depth of 10–20 mm with the stationary potential of the reinforcement, d) image of the reinforcement at a depth of 10–20 mm with the corrosion current density, e) image of the reinforcement at a depth of 10–20 mm with the resistivity of the concrete cover

influence on corrosion processes in reinforced concrete elements. Measurements of corrosion current density (the most authoritative parameter), which determines the corrosion activity of the bars, showed that in some of the tested bars of the loggia wall they exceeded $i_{cor} = 5\ \mu A \cdot cm^{-2}$ (reaching a maximum of $i_{cor} = 8.74\ \mu A \cdot cm^{-2}$), while in the interior wall a maximum of $i_{cor} = 4.86\ \mu A \cdot cm^{-2}$. This was slightly less obvious when comparing the values of the other two parameters: the measurements of the stationary potential of the reinforcement for both the loggia wall and the inner wall indicated a probability range of corrosion development from 5% to 50%, and based on the measurements of the concrete cover resistivity indicated a high probability of corrosion.

However, it is worth noting that improperly designed concrete cover, with a thickness too small, has a large impact on the progressive corrosion process of the reinforcement in the concrete. Although the results of the galvanostatic pulse measurements (especially the corrosion current density) obtained for the loggia wall are higher than those of the inner wall, these values do not differ significantly at most measurement points (for the reinforcement of the loggia wall and the inner wall at the measurement points where the concrete cover was thinnest, they are about $i_{cor} = 5\ \mu A \cdot cm^{-2}$). Table 1 lists the symbols and abbreviations used in this study.

CONCLUSIONS

Based on the research and analyzes carried out, it can be concluded:

1. The direct cause of the development of corrosion of the reinforcing bars (both the reinforcement of the internal wall of the building and the previously tested loggia wall) was too low thickness of the concrete cover - not made in accordance with the recommendations for the designed exposure classes, and the reinforcement was not properly protected.
2. The smallest measured cover thickness was max 10 mm, which means that the reduction in the cover thickness in some tested sections reached up to 50% – according to the standards in force at the time of construction of the building, the minimum concrete cover thickness should be 20 mm (currently 25 mm).
3. It was found that changes in subsequent standards regarding the design of concrete cover are more restrictive, forcing an increase in its thickness and a more detailed analysis of exposure conditions.
4. The reinforced concrete structures erected in the past have underestimated the cover parameters compared to current standards.
5. Current planned modernizations of large-panel buildings should be planned based on a comprehensive assessment of the scope of necessary repairs and renovations, including an assessment of the condition of the concrete cover and strengthening of structural elements.
6. The repair should consist not only in restoring the condition before the damage, but also in making the elements in accordance with the currently applicable standards (in particular, attention should be paid to such construction elements as loggias, balconies, columns, which are often not subject to modernization and which due to exposure to environmental conditions are exposed to a high risk of damage and reduce the durability of the entire structure).
7. The analysis of reinforced concrete elements in terms of durability should include all forms of reinforcement (not only the main reinforcement) because the initiation of corrosion on the secondary reinforcement may quickly lead to damage to the concrete cover and, consequently, accelerate the corrosion of the main reinforcement.
8. Repair work should be carried out with due care, striving to restore the cover thickness in accordance with the current standard.

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