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Modern digital technologies as support for classic measurement methods in corrosion diagnosis of reinforced concrete

Nowoczesne technologie cyfrowe jako wsparcie klasycznych metod pomiarowych stosowanych w diagnostyce korozyjnej żelbetu

This article presents contemporary methods for diagnosing corrosion damage in reinforced concrete structures. The first section provides a brief overview of traditional measurement methods used to assess the corrosion risk of reinforced concrete, including tests of concrete's protective properties against reinforcement, corrosion probability tests, and polarisation tests of the corrosion rate of reinforcement in concrete. The second part of the article describes modern digital technologies that support the diagnosis of corrosion damage, including visual inspection using mixed reality and artificial intelligence, and remote inspection using drones. Additionally, the article describes a BIM model of the diagnosed structure allowing for the creation of a digital twin. This model integrates all classical and digital diagnostic tools.

Keywords: reinforced concrete structures, corrosion, diagnostics, mixed reality, MR, augmented reality, AR, artificial intelligence, AI, drones, image analysis, BIM, digital twin

W artykule przedstawiono współczesne możliwości prowadzenia zaawansowanej diagnostyki uszkodzeń korozyjnych konstrukcji żelbetowych. W pierwszej części skrótowo omówiono standardowe metody pomiarowe, od dawna stosowane w ocenie zagrożenia korozyjnego żelbetu: badania właściwości ochronnych betonu względem zbrojenia, badania prawdopodobieństwa korozji i polaryzacyjne badania szybkości korozji zbrojenia w betonie. W drugiej, zasadniczej części artykułu scharakteryzowano nowoczesne technologie cyfrowe wspierające diagnostykę uszkodzeń korozyjnych: inspekcję wizualną z użyciem technologii rzeczywistości mieszanej i sztucznej inteligencji, a także zdalną inspekcję z wykorzystaniem dronów. Jako technologię integrującą wszystkie standardowe i cyfrowe narzędzia diagnostyczne opisano model BIM diagnozowanej konstrukcji, umożliwiający stworzenie cyfrowego bliźniaka.

Słowa kluczowe: konstrukcje żelbetowe, korozja, diagnostyka, rzeczywistość mieszana, MR, poszerzona rzeczywistość, AR, sztuczna inteligencja, AI, drony, analiza obrazu, BIM, cyfrowy bliźniak

1. Introduction

The naturally time-limited durability of any reinforced concrete structure requires facility managers to conduct periodic condition surveys. A properly planned diagnostic assessment for corrosion risk should include both concrete testing (including for protective properties with respect to the reinforcement) and polarisation tests of the corrosion rate of the reinforcement, possibly supplemented by potential and resistivity tests. However, especially in the case of large buildings, it is worth considering supporting "classical" diagnostics with modern digital technologies. The efficiency of the building inspector's work should increase when digital tools using so-called mixed reality supported by artificial intelligence are used. In the case of tall buildings or structures with difficult or dangerous access, the use of drones is worth additional consideration. Drones, after scanning an image of the surface condition of the structure under investigation, can provide valuable diagnostic material suitable for processing with image analysis methods. The buckle that binds modern corrosion damage diagnostics into one coherent whole is BIM technology, which makes it possible to implement the results of all tests and measurements into a digital representation of the examined object in the form of a BIM model.

This article outlines the impressive possibilities of modern digital technology, which, in combination with the currently used "classic"

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methods of corrosion diagnosis, can effectively support complex decision-making processes related to the safety assessment of building structures.

2. Classic measurement methods used in corrosion diagnosis of reinforced concrete

2.1. Testing the protective properties of concrete with respect to the reinforcement

This type of concrete testing has the aim of identifying the causes of potential corrosion of the reinforcement in concrete. The testing methodology always starts with the extraction of material from the structure, generally by either stratified grinding of the concrete or cutting concrete cores for stratified analysis under laboratory conditions.

In order to map the pore solution of the concrete, an aqueous extract is usually prepared by mixing the crushed concrete with distilled water. In a more accurate approach, vacuum extraction can also be carried out to concentrate the resulting aqueous extract or, alternatively, pressure extraction can be performed to extract the liquid phase from the concrete, but with properties that are unfavourably averaged across the sample.

Interpretation of the material test results involves the determination of the chloride content and pH value in the pore solution, which allows the extent of the chloride-contaminated or neutralised concrete zone to be determined. It is crucial to determine the critical pH level (11.8) and the limiting chloride concentration (0.4%), as values below or above these thresholds, respectively, may indicate the initiation of reinforcement corrosion in the concrete [1].

2.2. Investigating the probability of corrosion

Corrosion probability tests generally involve two methods: potential and resistivity measurements. Potential tests involve measuring the electrical potential of the reinforcement in the concrete using a millivoltmeter connected to a reference electrode and a test electrode, which is a steel reinforcing bar in the concrete. Resistivity testing, on the other hand, involves measuring with an ohmmeter the resistance of the concrete to a flowing direct current between two metal electrodes placed in holes drilled in the concrete cover.

The evaluation of the results from both methods is based on the analysis of contour maps plotted from measurements made in an orthogonal grid of points. For potential tests, a potential below −350 mV suggests a high probability of corrosion, and above −200 mV a very low probability. For resistivity tests, concrete resistivity below 10 kΩcm indicates a high probability of corrosion, while above 20 kΩcm a low probability. It should be emphasised that the methods described, which are characterised by simplicity in their technical implementation, are nevertheless strongly debatable in terms of a quantifiable assessment of corrosion risk [2].

2.3. Electrochemical polarisation investigations of the corrosion rate of the reinforcement

Three main electrochemical polarisation methods are used to assess the corrosion rate of the reinforcement in concrete: the linear polarisation resistance (LPR) method, the galvanostatic pulse (GP) method and the electrochemical impedance spectroscopy (EIS) method.

The LPR method measures the polarisation resistance, which is inversely proportional to the corrosion rate, by forcing small linear changes in the potential of the steel reinforcement. The GP method analyses the changes in potential of the reinforcing steel under the influence of a series of current pulses. The EIS method, on the other hand, examines the electrical response of the reinforcement excited by a sinusoidal current signal, with the impedance reflecting the resistance of the steel-concrete system to the flowing alternating current [3].

To carry out polarisation measurements on the structure under test, a three-electrode system is used, consisting of a potentiostat as the control and recording device, a reinforcement bar as the working electrode, a reference electrode, an auxiliary electrode and, optionally, a screening electrode to control the polarisation current spread. The polarisation resistance or charge transfer resistance values obtained from the analysis of the test results are inversely proportional to the corrosion current density, which is an indicator of electrochemical transformations, but does not directly define the degree of corrosion risk. Corrosion current densities below 0.5 mA/cm^2 indicate low or no corrosion, while values above 0.5 mA/cm^2 signal the development of corrosion processes [4].

3. Digital technologies to support corrosion damage diagnostics

3.1. Visual inspection supported by augmented reality and artificial intelligence

Supporting the classic visual inspection of the condition of structures with mixed reality (MR) and artificial intelligence (AI) opens up new possibilities for realising more efficient and accurate infrastructure assessments [5]. Using MR, inspectors can analyse defects (e.g. cracks, scratches) in real time, displaying real-time information on the dimensions and precise location of identified defects. This integration of MR technology with AI enables inspectors to collect more objective data while using their professional judgement, which is a significant advance over traditional inspection methods [6].

Virtual reality (VR) allows users to be completely immersed in a computer-generated environment, while augmented reality (AR) superimposes computer-generated images onto the real world. Mixed reality (MR) combines elements of VR and AR, allowing interaction with virtual and real objects in a single space. These technologies are supported by a variety of devices, such as VR goggles (Fig. 1), AR headsets and MR smartglasses, each offering different capabilities and levels of immersion [7].

Artificial intelligence plays a key role in the inspection process by facilitating the identification and analysis of structural defects. By employing machine learning and deep learning algorithms, AI can automatically recognise defect types, assess their severity and suggest potential corrective actions. Such systems can significantly improve the accuracy and objectivity of inspections, while reducing the time and costs associated with facility maintenance [8].

For MR-supported inspection to be effective, a number of technical and practical issues need to be addressed. Key challenges

Fig. 1. Visual inspection of corrosion damage supported by mixed reality and artificial intelligence

Rys. 1. Inspekcja wizualna uszkodzeń korozyjnych wspierana technologią rzeczywistości mieszanej i sztuczną inteligencją

Fig. 2. Scanning the location and type of corrosion damage on a silo shell using a drone

Rys. 2. Skanowanie lokalizacji i rodzaju uszkodzeń korozyjnych na płaszczu silosu za pomocą drona

include ensuring adequate accuracy and resolution of MR visualisation, integrating data from different sources in real time, and providing ergonomic and intuitive interfaces for the user [9]. The most challenging issues, however, are those related to the accuracy of AI's damage identification and classification under varying environmental conditions. It is worth emphasising that in diagnostic practice, the knowledge and experience of the inspector will continue to play a key role, even when aided by mixed reality tools [6].

3.2. Corrosion damage diagnostics using drones (UAV)

Remote inspection of structures using unmanned aerial vehicles (UAVs), known as drones, represents a significant advance over traditional visual inspection methods [10]. Drones open up new possibilities by allowing access to hard-to-reach areas, significantly speeding up the data collection process and providing high-resolution photographs and recordings [11]. This approach not only increases the efficiency and accuracy of inspections, but also increases the safety of inspectors by eliminating the need to expose them to hazardous conditions.

For drones to be effective in inspecting large building structures, they must meet certain technical requirements. It is crucial that they allow for a wide range of flight control, as well as being resistant to wind. Positioning precision, made possible by the use of RTK (real-time kinematics), is essential for accurate data collection. In addition, the high resolution of the camera and the large memory capacity are necessary to record the details of the structure under study. Autonomy and the ability to follow a pre-programmed flight path increase the efficiency of operations and minimise the need for human intervention (Fig. 2).

Despite its many advantages, the use of drones in the inspection of building structures faces limitations. Weather conditions, such as high wind or rain, can make inspections difficult or impossible. Regulations requiring permits to fly around a structure can prolong the preparation work. In addition, electromagnetic interference occurring around the structure can affect the performance of drone navigation systems.

The process of inspecting structures by drone can be divided into four main stages [12]. The first stage – reconnaissance and preparation – involves collecting data on the structure and assessing the conditions on site. This is followed by the second stage – image collection – where a drone flight is performed to collect the necessary data. The third stage – image processing and analysis – involves reconstructing a 3D model of the structure and identifying potential damage. The final stage – integration with the BIM model – allows the collected data to be implemented in a 3D model of the object under study. The third stage concerning image analysis proves to be the most difficult, requiring specialist knowledge and software. Data collection (in stage two), on the other hand, is the most time-consuming phase, especially on complex large-scale structures.

An interesting example of the use of remote inspection was the Monte da Virgem telecommunications tower, located in Vila Nova de Gaia, Portugal [12]. This tower is the tallest structure of its type in Portugal, with a height of 177 m. It consists of a 126 m long concrete stem, which has the shape of a rotating hyperboloid, and a 51 m high metal mast. The stem contains five technical floors, two of which are closed and three of which are open. The mast supports FM, VHF and UHF transmission systems.

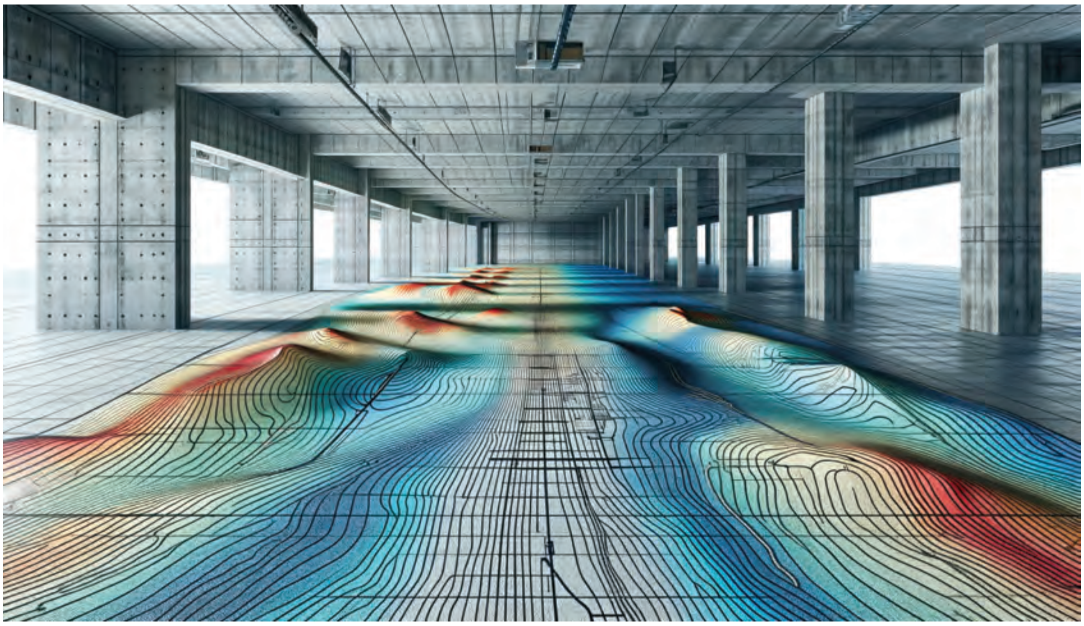

Fig. 3. Mixed reality mode view of a colour contour map of car park floor slab reinforcement corrosion potential displayed in real time to an inspector equipped with MR goggles during an inspection

Rys. 3. Widok w trybie rzeczywistości mieszanej barwnej mapy warstwicowej potencjału korozyjnego zbrojenia płyty stropowej parkingu wyświetlany w czasie rzeczywistym inspektorowi wyposażonemu w gogle MR w trakcie inspekcji obiektu

Inspection of the exterior of the tower stem, at heights ranging from 5 m to 60 m, was carried out using a DJI Matrice 600 Pro drone with a DJI Zenmuse X5 camera. Image collection was done manually, from different angles and heights, with minimal image overlap. Image processing was performed using Pix4Dmapper, creating a 3D model of the structure. Image analysis using MATLAB© Image Processing Toolbox allowed the identification of biological colonies, corrosion of reinforcement, efflorescence and any visible cracks. Defects were most prevalent on the eastern side of the stem and were associated with less sun exposure.

The integration of the diagnostic survey results with the BIM model was carried out on the Autodesk Revit platform, which enabled an accurate analysis of the condition of the structure and maintenance planning. The remote drone inspection method confirmed the effectiveness of identifying potential problems and, according to the study authors, can be successfully applied to monitor other tall structures in the future.

3.3. Implementation of identified structural defects in the BIM model

The implementation of degradation parameters obtained from corrosion diagnostic tests into the BIM (building information modelling) model of the structure under study allows for a significant improvement in the maintenance and upkeep processes of building infrastructure. It is worth referring at this point to the multidimensionality of BIM models, which divides them into 3D, 4D, 5D, 6D and 7D models [13]. Each of the models refers to different aspects of construction project management, i.e. from visualisation to cost and schedule management to sustainability and operational building management. Corrosion diagnostics, a key element in long-term structural safety management, fits perfectly into the concept of the 7D model, which focuses on the building operation and maintenance phase. The implementation of diagnostic data into the BIM model (e.g. depth of concrete carbonatation, chloride content of concrete, contour maps of the corrosion potential of the reinforcement, etc.) allows for precise planning of maintenance and repair works, minimising the cost and time required to carry them out.

Fig. 3 shows an example visualisation of an image seen by an inspector equipped with MR goggles entering a multi-storey garage of a reinforced concrete structure. The results of the potential survey of the garage floor slab, previously entered into the BIM 7D model, are displayed to the inspector as a mixed reality during the visual inspection of the structure. On the potential contour map, zones coloured red and orange indicate a high probability of corrosion, while zones coloured blue and green signal a low probability.

4. Conclusion

This paper presents a concept for modern corrosion damage diagnosis of reinforced concrete structures. It includes the implementation of classical corrosion tests, with the support of mixed reality and artificial intelligence, as well as remote inspection by drones. It is also recommended that degradation characteristics, acquired by the methods described above, be introduced into BIM models of the structures under investigation.

In the context of the increasingly popular concept of the digital twin [14], the BIM model enriched with diagnostic corrosion data becomes a key element of the digital representation of the physical structure, enabling detailed analysis of its condition and behaviour over time. The digital twin, using data from the BIM model, can be used not only to monitor the condition of a structure, but also to simulate various repair and maintenance scenarios [15], which has a direct impact on improving the efficiency of the management of building infrastructure.

CRediT authorship contribution statement
Mariusz Jaśniok: Conceptualization, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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