Garden building diagnostic systems for sustainable preservation

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***Abstract*—A garden building located in Torino, 25 VERDE, designed by the architect Luciano Pia is object of a monitoring diagnostic campaign, started in 2016 and still in progress, for ensuring a long-lasting sustainable preservation. The residential complex of sixty-three apartments conceived as a habitable forest in which almost 200 trees cut down the fine dust caused by cars, is characterized by irregularly shaped terraces, supported by weathering steel tree-like structures. The weathering steels or high-strength low alloy steels have a unique interesting characteristic: they corrode under proper environmental conditions, forming a compact and tightly adherent oxide barrier that seals out the atmosphere and retards further corrosion. Dry and wet cycles create a protecting patina layer, meanwhile the constant presence of humidity and of aggressive gaseous pollutants (SO_2, NOx, etc) in the atmosphere degrades the properties of the layer. The diagnostic intervention is centered in the monitoring of the weathering steel structures by means of in situ electrochemical techniques, as Electrochemical Impedance Spectroscopy (EIS). The experimental data confirm that the high sensitivity and low invasiveness of EIS makes it a powerful technique for corrosion assessment of metallic structures exposed outdoor.**

***Index Terms*—Green architecture, EIS, corrosion, in situ monitoring**

I. INTRODUCTION

Eco-sustainable architecture often uses greenery as a design tool to improve the performance of the building, reduce its impact on the environment and increase the comfort of the inhabitants [1]. As a matter of facts, vegetation may offer several advantages to buildings, as the benefits of green roofs or walls, which improve the local microclimate, the insulation of the building and reduce the heat island effect. The structural and natural element strongly affect the housing environment quality and its evaluation [2]. Green spaces have a positive impact on the quality of the lives and work of people. Nature is considered a curing element, it allows to increase creativity and productiveness; at the same time it reduces stress, rage, anxiety, improving thus, overall health and well-being [3] [4]. Depending on the objectives, needs and characteristics of the building, the greenery can be inserted in different ways. The increasing number of green buildings demonstrates the success of the idea of integrating nature with architecture [5].
The studio of architect Stefano Boeri designed the first Bosco Verticale in Milan, a building that has become not only the symbol of the city, but an example to be emulated and re-proposed in different places around the world [6]. The inauguration dates back to 2014 and the building houses a total of 800 trees of different sizes. It is a prototype, a model that emphasizes the importance of human well−being, without forgetting the relationship with nature and the respect of it. The intense presence of vegetation, comparable to that of almost 30,000 m^2 of forest, brings benefits to air quality and microclimatic control, as well as a spectacular change in the facades over the seasons. Now, around the world, there are several vertical forests and Boeri, in Liuzhou, China, designed the next level to the vertical forest: the Forest City [7], an ambitious example of urban forestry, shown in Fig. 1.

In Germany in Dusseldorf stands the Kö-Bogen II office building designed by the Ingenhoven architecture firm, largely covered with vegetation, which gives life to one of the largest green facades in the world. It is a multifunctional building that houses spaces dedicated to culture, offices and commerce, for a total of 42,000 m^2. The aim of the German architectural

Fig. 1. The Forest City in the Chinese city of Liuzhou, designed by Stefano Boeri architecture studio.

Fig. 2. Kö-Bogen II office building, in Dusseldorf, in Germany, designed by Ingenhoven architecture firm.

Fig. 3. The building of the California Academy of Science, in Dusseldorf, in Germany, designed by Renzo Piano architecture studio.

Fig. 4. The building "25 VERDE" in Turin, in Italy, designed by Luciano Pia architecture studio.

firm was to "restore as much green as possible to the city". The facades are lined with hornbeam hedges resistant to harsh climatic conditions and which do not require much maintenance and care, ensured by an integrated irrigation and drainage system, Fig. 2. This expanse of greenery guarantees a high CO_2 absorption capacity, a fundamental aspect in any city, and favors the reduction of temperatures in summer, often raised by the strong presence of concrete and other waterproof materials.

The California Academy of Science, designed by Renzo Piano, is a research institute and museum of natural history and science in San Francisco. The building is located within the Golden Gate Park and was built with the objectives of sustainability and respect for the environment, as a matter of facts, the materials are recyclable and renewable sources are used [8]. The green roof allows the California Academy of Science to integrate into the surrounding landscape, since its undulating shape also recalls that of the nearby hills. The green roof extends for about 60,000 m^2, absorbs most of the rainwater and is certainly one of the elements that characterizes the project, Fig. 3. The design of the green was carried out in collaboration with a botanist, planting almost two million seedlings of native species.

In Turin, the architect Luciano Pia designed and realized in 2012, the "25 VERDE", a residential complex of 63 apartments conceived as a habitable forest in which almost 200 trees cut down the fine dust caused by cars, protect from noise, create an ideal microclimate inside the building by mitigating the changes in temperature in summer and winter and blend with the architecture becoming an integral part of it, Fig. 4. Designed to be introspective and pleasant to live inside, it was made with natural materials, wisely used to create a unique and spectacular effect. The irregularly shaped terraces are supported by weathering steel tree-like structures and the wooden and glass flooring has been designed to allow light to filter from one floor to another. The entire building is clad with wooden shingles to evoke the bark of trees; lush gardens cover the roofs with greenery and a large courtyard hosts a wood-garden on the ground floor. The well-being that living in a "green" environment generates in this case is tangible: considerable mitigation of external temperatures, over 5 tons/year of CO_2 absorbed for the same amount of oxygen produced and finally almost 1.5 kg/year of fine dust reduced. One of the objectives now achieved was to obtain maximum energy efficiency. Numerous integrated solutions have been adopted: "external coat" insulation, ventilated walls,

Fig. 5. Map of the ground floor of 25 VERDE (top) and pictures of the building (bottom).

Fig. 6. The map of the second floor of 25 VERDE (top) and picture of the façade (bottom).

protection from direct solar radiation, heating and cooling systems with single metering of consumption, using ground water and the heat pump system. In addition, there are also features of thermal insulation and maximum efficiency of the heat and cold generation systems with savings of 40%-50% compared to the use of traditional systems. Nothing is wasted: total energy recovery and simultaneous reuse of heat in the building-plant system, recovery of rainwater, storage and reuse for irrigation of greenery.

25 VERDE is characterized by a multi-faceted green and the areas of intervention are different: flower boxes on the terraces, internal courtyard garden, green roof in the mezzanine area where the lofts overlook, green roof on the roof. In particular, the weathering steel planters in the shape of an inverted truncated cone house, depending on the size, trees or shrubs; the heights available are also different and range from 2.5 m in height to over 8 m. Primarily deciduous species were chosen, to allow solar radiation in the winter. Taking into account the specific exposure of each terrace and the spaces available, different plants were used for their habit, for example, conical trees such as *Liquidambar styraciflua* and *Carpinus betulus* were chosen; at the base of the trees, ground cover species, easy to maintain have been planted. The garden courtyard, surrounded on three sides by the building, is characterized by larger trees and is crossed by pedestrian passages, made in the trenches: the greenery is raised by more than a meter with respect to the floor and is not accessible except for maintenance care. The greenery, designed to recreate a miniature forest, develops on four levels: first and second size trees as *Ginkgo biloba, Acer platanoides and third size trees as Acer japonicum*; native shrubs. The top floor of the building is a roof garden, divided into as many properties as there are apartments on the top floor. These gardens are private and a spiral staircase in weathering steel facilitates access from the terraces on the fifth floor.

25 VERDE is the object of this paper that deals with the application of diagnostic systems for a long-lasting sustainable preservation.

As well known, various types of building diagnostic techniques are available aimed at highlighting the structural conditions of buildings which, deteriorating over time, could cause irreparable damage with major safety problems [9]. Therefore periodic inspections and building condition assessment for diagnostic purposes are strongly recommended, to be carried out by experts with knowledge of structural engineering, materials and testing [10]. The inspection may consist of a visual inspection, deflection measurement, failure measurement, crack mapping, as well as observations of traces of water leaks, evaluation of oxygen content [11], and corrosion of the metal alloys used, usually steel, meanwhile the condition assessment generally includes the taking of samples for chemical-physical tests on materials [12], in situ measurement of temperature and humidity [13], electrical potential of the half-cell, vibrations and delamination and occasionally continuous monitoring of the above-mentioned parameters [14]. The data collected from all these tests should make it possible to express an opinion on the overall structural condition in terms of expected residual life and to suggest any repairs.

Among the non-invasive measures that exploit electrical impedance, the electrical impedance tomography (EIT) is an innovative solution for determining dampness distribution in walls affected and historical buildings [15]. The measurements of electric potential distribution on the surface under examination allows to obtain the distribution of electrical conductivity the masonry, which is connected to the dampness of the specific internal structure of the investigated element [16].

In the case of 25 VERDE, our diagnostic intervention, Fig. 5 and Fig. 6, was centered in the monitoring of the weathering steel structures by means of in situ electrochemical techniques, as Electrochemical Impedance Spectroscopy (EIS) [17] [18]. The ultimate goal is to understand and assess the effect of the exposure conditions to the atmospheric corrosion of the weathering steel in these modern heritage buildings and structures [11] [19]. The paper presents the electrochemical results collected during an in situ monitoring campaign started in 2016 and still running.

II. MATERIALS AND METHODS

EIS measurements were carried out by means of a portable commercially available electrochemical interface (Ivium-CompactStat.e 10800) able of measuring impedance values in the range of 10 Ω to 1 TΩ, with modulus uncertainty lower than 5%, and with a phase uncertainty lower than 3°.

The EIS measurements were carried out in Na_2SO_4 0.1 M solution, in the frequency range of 0.01 Hz to 100 kHz, by stimulating the sample with a small alternating voltage, in the range from 10 mV - 100 mV, while compensating the open corrosion potential (E_{OCP}). The measuring probe, shown in Fig. 7, is a two-electrodes cell designed to be easily positioned on the metallic surface by means of a double-side bonding tape and easily removed. The probe realized by means of a 3D printer, (30 mm in diameter, 20 mm thick) is made of Acrylonitrile Butadiene Styrene (ABS); its measuring round-shape surface area is 8 mm in diameter. The probe with a platinum (Pt) wire, as the reference/counter electrode, and the weathering steel as working electrode, is equipped with a 2 mm thick adhesive polyurethane disk, which allows its positioning also on non-perfectly flat vertical surfaces. The electrolytic solution, about 1 cm^3, is injected through the inlet tube, while the air flows out from the cell thought the outlet tube.

III. RESULTS AND DISCUSSION

Thanks to the visual inspection, the primary step of every building inspection, the monitoring points were identified, as shown on the maps of ground floor and of the second level of the building, Fig. 5 and Fig. 6. Particular attention has been paid to the appearance of the structural and non-structural components of the building, observing the presence

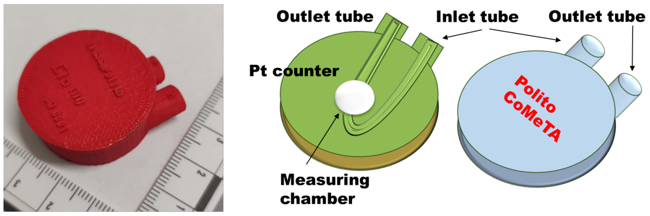

Fig. 7. Two-electrode probe for EIS measurements in situ, applicable on both slanted and vertical surface. On the left, the 3D printed ABS probe used for metallic surface measurements.

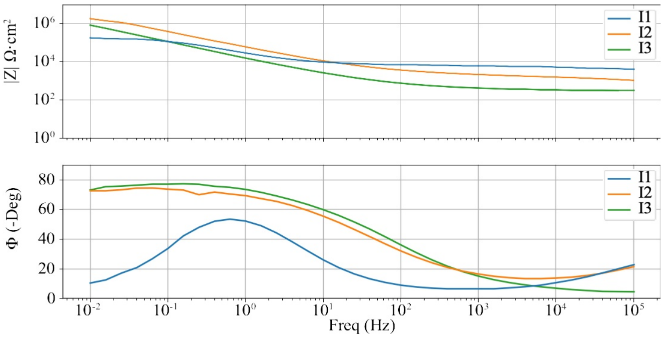

Fig. 8. Bode plots of EIS measurements collected on a weathering steel load-bearing structure located in the building interior.

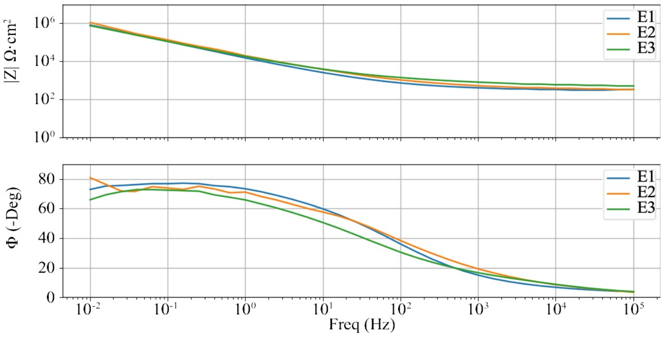

Fig. 9. Bode plots of EIS measurements collected on a weathering steel trunk shaped column placed in the exterior part of the building.

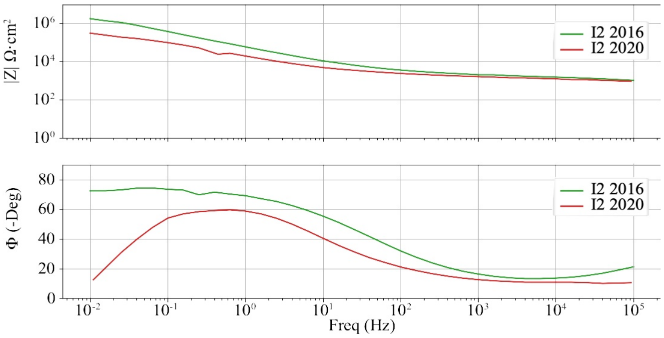

Fig. 10. EIS measurements collected in 2016 and 2020 on a weathering steel structure located in the building interior.

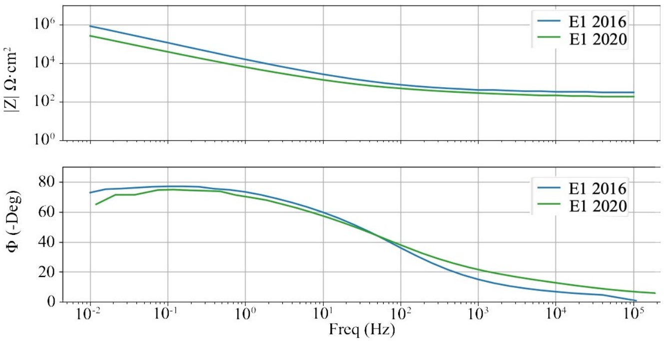

Fig. 11. EIS measurements collected in 2016 and 2020 on a weathering steel structure in the exterior part of the building.

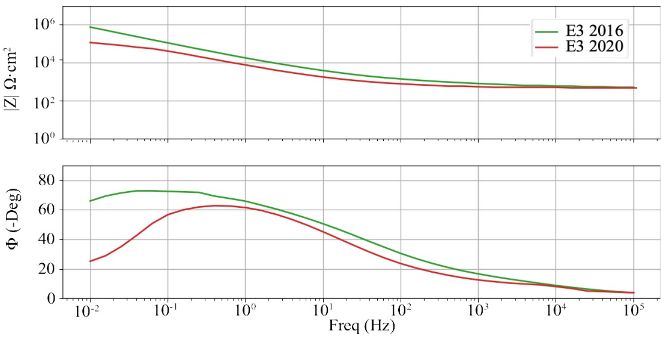

Fig. 12. EIS measurements collected in 2016 and 2020 on a weathering steel structure in the exterior part of the building.

of cracks, any signs of water leakage and weathering steel color variation. As a matter of facts, the steels employed in this building are weathering steels (CORTEN) or high-strength low alloy steels with a unique interesting characteristic: they corrode under proper environmental conditions, forming a compact and tightly adherent oxide barrier that seals out the atmosphere and retards further corrosion [20]. Weathering steels behave differently from the other steels which are subject to well-known corrosion processes, that induce the formation of a non-protecting coarse, porous and flaky oxide. The corrosion-retarding effect of the protective layer is due to the presence of the alloying elements, as Cu, Cr, Ni, Mn, etc., whose percentage ranges between 0.2–0.3 wt% [21]. In the weathering steels, rust develops and regenerates continuously in dependence of the atmospheric exposure: dry and wet cycles create a protecting patina layer, meanwhile the constant presence of humidity and of aggressive gaseous pollutants (SO_2, NOx, etc) in the atmosphere degrades the properties of the layer. In the design and realization of structures in weathering steel it has to be avoided the accumulation of water in interstices, that certainly should experience higher corrosion rates, provision for drainage is mandatory, furthermore weldments could require special welding techniques or materials [22] [23].

The EIS diagnostic campaign was performed on different weathering steel structures of 25 VERDE in distant years. In particular, six specific structures were investigated: three trunk shaped columns placed in the exterior of the building, and three load-bearing structures located in the building interior. The measurements were carried out on different areas of the previously mentioned structures, which showed rust layers of different colors and morphology. Thus, different corrosion behaviors were observed, as highlighted by different values of the impedance modulus, $|Z|$, which can be correlated to the corrosion process arising at the rust layer/metal interface. This latter, is directly linked to the electrochemical stability of the rust layer, the higher impedance modulus, the higher is the electrochemical stability. A good electrochemical stability of the rust layer provides a better protective efficiency against further corrosion. All impedance spectra are scaled to an equivalent area of 1 cm^2. The impedance spectra collected on the weathering steel load-bearing structures placed in the interior of the building, one of them close to a small pool, are shown in Fig. 8. In particular, the measurements performed on the I2 area, as well as on I3 structure, show a high impedance modulus at low frequencies and a pure capacitive behavior. The protective rust layer, well adherent to the metallic surface, offers a good retarding action towards further corrosion. Thanks to the solid brown-black colored corrosion products layer, due to the high Cu percentage of the weathering steel analyzed in this case. On the other hand, a different electrochemical behaviour has been observed on the I1 structure, which is characterised by a lower impedance modulus. Moreover, the impedance phase, assessed on the area I1, shows diffusion phenomena at low frequency, connected to the poor insulating properties of the analyzed rust layer. Above all, the closeness of the pool of the I2 structure limits the formation of a homogeneous protective rust layer on the entire weathering steel surface, which cannot reach a stability. Fig. 9 shows the measurements collected on the weathering steel tree trunk shaped columns on the exterior of the building, which present a protective corrosion products layer due to the exposure conditions. Particularly, sunlight and fast wet/dry cycling enable the formation of a protective rust layer, as described in literature [24]. Hence, the EIS spectra of Fig. 9 present a more homogeneous electrochemical behavior of rust patina, characterized by a pure capacitive behaviour with by high impedance modulus values at low frequency.

The same measurements were repeated after few years.

Fig. 10 shows the impedance spectra recorded on the weathering steel surface of the interior structures measured in 2016 and 2020, in particular the aforementioned area I2. Over years, the surface exposed in the interior of the building shows a lowering of the protective capacity of the rust patina, indeed, the impedance modulus value is lowered. This behavior highlights that the patina has not yet reached its stability; this is due to the proximity of the pool of the interior area, and the impossibility of guaranteeing inside the building the normal wet/dry cycle which enables the formation of a protective rust layer. In fact, in the graph that represents the comparison of the measurements made on the external surfaces of the building, in particular as an example in the area E1, Fig. 11, shows the same impedance behaviour over the time, hence, an appreciable stability of the patina and, therefore, a greater protective capacity is appreciable. However, measurements collected on another point of the exterior building, area E3 of Fig. 12, over the time, show a higher sensitivity to the corrosion due to the different exposition to the atmospheric conditions.

IV. CONCLUSIONS

Regardless of the either physical or geographical conditions in which human beings find themselves, they have an innate tendency to seek connections with nature. The more they detach from the wild, the more they develop means and strategies to bring nature back into their daily life.

The garden building 25 VERDE is part of a strategy that identifies in the vertical dimension a possibility to foster the use of vegetation in urban areas. Due to their unmatched ability to absorb CO_2, planting trees is often viewed as one of the best carbon offsetting solution, consequently the green architecture is a rising trend in urban landscapes, mainly in cities with limited available plots of land as Tokyo and New York. For a sustainable preservation of these buildings, due to the variety of typologies of materials and solutions utilized by architects, tailored diagnostic systems have to be employed. In the case of 25 VERDE, where the utilization of weathering steel is predominant with respect to metallic materials, in situ Electrochemical Impedance Spectroscopy measurements have been employed to evaluate the protective effectiveness of the surface oxides developed on the structures.

As a matter of facts, the ability of weathering steels to develop homogeneous and protective corrosion products layers is strongly dependent on the environmental exposure conditions.

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REFERENCES

[1] T. Hartig, G. W. Evans, L. D. Jamner, D. S. Davis, and T. Gärling, “Tracking restoration in natural and urban field settings,” *Journal of environmental psychology*, vol. 23, no. 2, pp. 109–123, 2003.

[2] I. Alcock, M. P. White, B. W. Wheeler, L. E. Fleming, and M. H. Depledge, “Longitudinal effects on mental health of moving to greener and less green urban areas,” *Environmental science & technology*, vol. 48, no. 2, pp. 1247–1255, 2014.

[3] J. Barton and J. Pretty, “What is the best dose of nature and green exercise for improving mental health? a multi-study analysis,” *Environmental science & technology*, vol. 44, no. 10, pp. 3947–3955, 2010.

[4] K. Modi and S. Parmar, “Understanding biophilia and its integration with architecture.,” *International Journal of Scientific and Engineering Research*, vol. 11, no. 5, pp. 1403–1440, 2020.

[5] P. Haupt, “Integrated urban landscape: nature as an element of transition space composition,” in *Back to the Sense of the City: International Monograph Book*, pp. 73–83, Centre de Política de Sòl i Valoracions, 2016.

[6] A. Ishween, “Grays to greens: A place where humans and nature coexist a case study of bosco verticale, milan, india,” *Descriptio*, vol. 3, no. 1, 2021.

[7] A. Kucherova and H. Narvaez, “Urban forest revolution,” in *E3S Web of Conferences*, vol. 33, p. 01013, EDP Sciences, 2018.

[8] V. Peyronel, “Environmental quality of the outdoor spaces of museums as a tool to increase awareness of environmental issues,” *Academia*.

[9] A. Kwan and P. Ng, “Building diagnostic techniques and building diagnosis: the way forward,” in *Engineering Asset Management-Systems, Professional Practices and Certification*, pp. 849–862, Springer, 2015.

[10] J. Hoła and K. Schabowicz, “State-of-the-art non-destructive methods for diagnostic testing of building structures—anticipated development trends,” *Archives of civil and mechanical engineering*, vol. 10, no. 3, pp. 5–18, 2010.

[11] L. E. Sebar, L. Iannucci, C. Gori, A. Re, M. Parvis, E. Angelini, and S. Grassini, “In-situ multi-analytical study of ongoing corrosion processes on bronze artworks exposed outdoors,” *Acta IMEKO*, vol. 10, no. 1, pp. 241–249, 2021.

[12] L. E. Sebar, L. Iannucci, Y. Goren, P. Fabian, E. Angelini, and S. Grassini, “Raman investigation of corrosion products on roman copper-based artefacts,” *Acta IMEKO*, vol. 10, no. 1, pp. 129–135, 2020.

[13] S. G. Leonardi, M. Bonyani, K. Ghosh, A. K. Dhara, L. Lombardo, N. Donato, and G. Neri, “Development of a novel cu (ii) complex modified electrode and a portable electrochemical analyzer for the determination of dissolved oxygen (do) in water,” *Chemosensors*, vol. 4, no. 2, p. 7, 2016.

[14] E. Angelini, C. A. Posada, E. Di Francia, S. Grassini, L. Iannucci, L. Lombardo, and M. Parvis, “Indoor and outdoor atmospheric corrosion monitoring of cultural heritage assets,” *Metallurgia Italiana*, vol. 4, pp. 34–41, 2018.

[15] J. Hoła, Z. Matkowski, K. Schabowicz, J. Sikora, K. Nita, and S. Wójtowicz, “Identification of moisture content in brick walls by means of impedance tomography,” *COMPEL-The international journal for computation and mathematics in electrical and electronic engineering*, 2012.

[16] T. Rymarczyk, J. Sikora, and P. Tchórzewski, “Implementation of electrical impedance tomography for analysis of building moisture conditions,” *COMPEL-The international journal for computation and mathematics in electrical and electronic engineering*, 2018.

[17] S. Grassini, S. Corbellini, E. Angelini, F. Ferraris, and M. Parvis, “Low-cost impedance spectroscopy system based on a logarithmic amplifier,” *IEEE Transactions on Instrumentation and Measurement*, vol. 64, no. 5, pp. 1110–1117, 2014.

[18] D. Ribeiro and J. Abrantes, “Application of electrochemical impedance spectroscopy (eis) to monitor the corrosion of reinforced concrete: A new approach,” *Construction and Building Materials*, vol. 111, pp. 98–104, 2016.

[19] E. Angelini, S. Grassini, M. Parvis, and F. Zucchi, “An in situ investigation of the corrosion behaviour of a weathering steel work of art,” *Surface and Interface Analysis*, vol. 44, no. 8, pp. 942–946, 2012.

[20] L. Zhou, S. Yang, Y. Dong, W. Zhang, J. Ding, G. Liu, C. Shang, and R. D. K. Misra, “Characterization of compactness of rust layers on weathering steels by an adsorption/dehydration test of ethanol,” *Acta Metallurgica Sinica (English Letters)*, vol. 33, no. 6, pp. 846–856, 2020.

[21] J. Deepak, V. B. Raja, and G. S. Kaliaraj, “Mechanical and corrosion behavior of cu, cr, ni and zn electroplating on corten a588 steel for scope for betterment in ambient construction applications,” *Results in Physics*, vol. 14, p. 102437, 2019.

[22] M. Morcillo, I. Díaz, B. Chico, H. Cano, and D. De la Fuente, “Weathering steels: From empirical development to scientific design. a review,” *Corrosion Science*, vol. 83, pp. 6–31, 2014.

[23] V. Kucera and E. Mattsson, “Atmospheric corrosion,” *Corrosion mechanisms*, vol. 28, pp. 211–284, 1987.

[24] M. Morcillo, B. Chico, I. Díaz, H. Cano, and D. De la Fuente, “Atmospheric corrosion data of weathering steels. a review,” *Corrosion Science*, vol. 77, pp. 6–24, 2013.