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**Research Article**

# The protection of reinforced concrete structures: Active and passive systems

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## Abstract

The conservation state, maintenance, repair, and complete restoration of reinforced concrete structures are recurring actions necessary to preserve the built infrastructure. A big issue related to enormous costs aimed at extending the service life of construction systems and addressed to sustainability. In the investigated cases of buildings and civil engineering structures, active and passive protection methods are presented. Both exhibit advantages and disadvantages that need to be accurately studied in order to make a correct and durable choice. Generally, active systems are often used in harsh environmental conditions, where more forms of localized corrosion take place, while passive methods are often utilized where the degradation and the structures are less adversely affected by intense degradation phenomena.

## Introduction

Corrosion is an electrochemical process that implies oxidation and reduction reactions on the metal surface [1]. In most cases, especially in buildings, the deterioration is mainly caused by concrete carbonation. This leads to a lowering of the pH of the concrete pore solution down to 9. The oxide passive film on the steel rebars becomes unstable. Furthermore, the presence of Oxygen and water dissolve the Iron into the solution and Iron hydroxide is formed. A further chemical reaction leads to the formation of FeOOH, so-called rust. The formation of the corrosion products and the increase in the volume take place homogeneously along the rebar surface and is relatively slow with time. Cracking and spalling of the concrete cover occur. Consequently, the rebars are directly exposed to the atmosphere, thus accelerating their degradation. The corrosion process can be monitored through electrochemical potential measurements. Usually, restoration works can be started before the safety of the structures is endangered.

A more dangerous and invasive form of damage is observed when chlorides enter the infrastructure. In this case, localized corrosion occurs and the diameter of the steel rebars can be easily reduced with a loss of the static requirements. This is particularly seen in tunnels, bridges, desalinization plants, park garages, swimming pools, highway elements, walls, and other artifacts subjected to chloride-rich detrimental environments [2]. Within the pits, the local chloride attack causes an acidification of the environment, that may reach pH < 6 and Oxygen depletion.

The restoration and protection of reinforced concrete structures can be achieved with active systems [3,4]. The electrochemical re-alkalinization is a possible restoration way. It consists of the cathodic production of $OH^-$ around the steel rebars. In addition, an alkaline solution is forced to penetrate the cementitious materials. The system must be applied to the structures for 1-2 weeks. Nevertheless, the low alkalinity penetration must be considered. The current requirements may vary between 500 and 2’000 $mA/m^2$. Electrochemical chloride removal also belongs to the active repair methods [5]. An electric field between the rebar and a Titanium electrode net is applied. The current requirement ranges between 500 and 1’000 $mA/m^2$. The application of the system may last

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for 2-3 months, depending on the infrastructure. The main disadvantages are complex monitoring and the incomplete removal of the chlorides. The third active system is cathodic protection. A direct current is applied between a Titanium anode and a cathode, i. e. the rebars. It is important to avoid any direct contact between the anode and the cathode. This system is applied permanently and the current requirement mainly ranges from 5 to 20 mA/m². The corrosion is largely reduced or stopped. The system is adjustable and the chlorides are removed from the rebars. Concrete must not be eliminated and alkaline re-passivation takes place around the rebars. In fact, the durability of up to 50 years can be achieved. On the other hand, the adverse effects that need to be taken into account are Hydrogen production and consequently the embrittlement as well as the stress corrosion cracking of the rebars. These events are especially critical in pre-stressed steel cables and tendons, where the system is not allowed. The acidification around the anode must also be checked. This occurs with currents above 90 mA/m². Therefore, constant monitoring of the system is necessary.

Passive protection systems exhibit several steps, techniques, and methods to accomplish a medium to long-term service life [6]. Active systems, require a detailed investigation of the conservation state of the infrastructure in order to obtain an adequate restoration of the different parts of a structure. They usually require the elimination of the damaged or contaminated cement-based material, cleaning of the corroded steel rebars, the application of protection paints, the repopulation with mortar, and the use of organic coatings or hydrophobic agents.

This work focuses on the use of active and passive protection systems for reinforced concrete structures. A critical overview of the application for some types of structures is given. The choice of the restoration method, as well as the long-term protection, is explained by comparing the systems from the point of view of the type and intensity of the deterioration, the exposure condition as well as the technical issues, and the costs that need to be considered.

## Experimental procedure

The conservation state of the concrete was determined by conventional investigation techniques for the determination of the compressive strength [7], the carbonation depth [8], the chloride content [9] and visual inspections. The corrosion stage and the active protection state were carried out with stray current monitoring, respectively with cathodic protection techniques [3].

## Results and discussion

### Protection with an active system

The cathodic protection of concrete structures is a protection method widely used for some types of structures, especially where a harsh environment dominates. The reliability of this technique is based on electrochemical criteria and it is not directly linked with visual inspections. A depolarization criterion indicates that 4 hours after the turn off of the direct current system, the electrochemical potential needs to move in the positive direction for at least 100 mV. In addition, the rebar potential after the turn-off must be more negative than $U_H < -0.5$ V. One day after the turn-off, the potential has to move in the positive direction for at least 150 mV. In this concern, the chloride content and the pH of the concrete may render the interpretation of these criteria more difficult [3,10].

### Buildings

In a sports building with a mixed structure of concrete and ceramic elements, water infiltrated from the flat roof. Rebar corrosion took place until a medium-advanced stage. Concrete cover spalling occurred and a partial roof elements detachment was observed (Figure 1 left). The corrosion products were removed and the rebars were cleaned. The humidity state of the upper layers was unknown. The concrete was completely carbonated. The complete removal of the concrete was not possible without the makeover of the entire roof. For the above-mentioned reasons, a cathodic protection system was installed. A new mortar was sprayed only along the rebars. The Titanium bands followed the steel rebars (Figure 1 right) and were covered with a second layer of mortar. The system was connected to a direct current source.

### Bridges

Bridges are among the infrastructures mostly subjected to detrimental substances, such as chlorides. A bridge located in the South part of the Alps exhibited highly contaminated concrete. The chlorides were spread on the structure during the Wintertime. A pile was restored by applying a Titanium net covered with mortar (Figure 2 left). A cathodic protection system was put in service in 1988 (Figure 2 right).

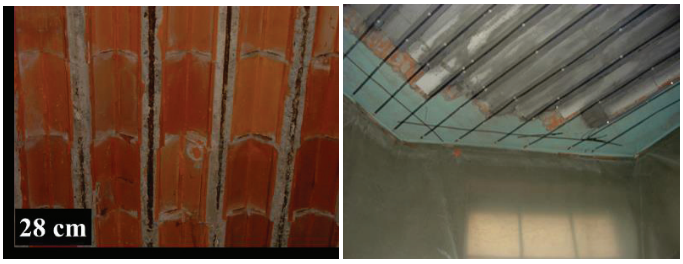

**Figure 1:** Ceramic roofing elements alternated by mortar layers. Corrosion and exposition of the steel rebars (left) and Titanium bands placed along the rebars covered with mortar (right).

**Figure 2:** Titanium net fixed on the concrete of the pile with white plastic dowels (left) and restored bridge pile (right).

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## Stray currents

Stray currents adversely influence the electrochemical potential and the corrosion of reinforced concrete structures. This fact is observed in large structures, which are partially buried in the ground. A direct current source supplies the electricity to a train. Part of the currents is dispersed into the ground. They try to find a way with low electrical resistivity to get back and close the loop to the original source. In the zones where the currents enter the structures, a lowering of the electrochemical potential takes place and protection occurs. Then, the current propagates within the structures, and in the regions close to the source they tend to exit from the metallic parts, thus causing a shift of the potential in the anodic direction and intense corrosion. In order to mitigate the metal degradation, cathodic protection can be installed. It may be adjusted according to the rebar potential variation due to the stray current influence. Furthermore, a general increase in the electrical resistance through insulating junctions or coatings as well as drainage with a direct electrical connection to railway lines may contribute to lowering or eliminating the adverse influence of the currents. With a direct current source, as in the case of some railway lines, the maximum mean potential variation must not exceed + 500 mV within a defined time span. This value is valid for not deteriorated concrete. In the case of high chloride contaminated or carbonated concrete, the maximum mean potential variation must not exceed + 100 mV [11]. For alternate current sources, the critical influence appears to start from 30 mA/m², although some aspects are still under clarification.

The steel rebars of a reinforced concrete highway bridge located above a direct current mountain railway line source were investigated (Figure 3). At a distance of 800 meters, an alternate current railway source was present. The pile rebar potential variation with time was monitored for the direct (red line) and alternate (blu line) current influence. The electrochemical potentials exhibited multiple shifts in the anodic direction (Figure 3 center), while after inserting electrical drainage, no relevant shifts were detected (Figure 3 right). This was particularly seen for the direct source, where the interference reduction was clear.

Similarly, monitoring of the stray current interference was done for a reinforced concrete basement of noise barriers along a highway (Figure 4 left). A train station was located in the vicinity. Alternate and direct current sources were present. The concrete basement was 3800 meters long. Anodic and cathodic shifts of the rebar potential were seen in some sectors of the basement depending on the train movements (Figure 4 center-right).

The cathodic protection system to be installed may be actively adjustable with no additional protective coatings on concrete. The system can be divided into sectors and activated in the case of needs. A Titanium impressed current anode placed along the concrete basement supplies the necessary protection current in the part of the infrastructure subjected to current exit (Figure 5).

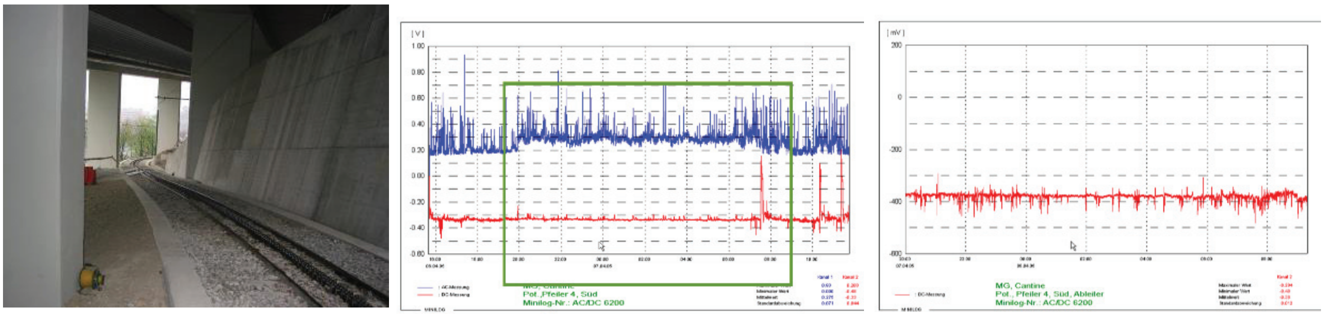

**Figure 3:** Railway and bridge position (left). The electrochemical potential of the rebars with time is influenced by the stray current (red line) and alternate current (blu line) generated by the train movements. Influence on the steel pile rebar's potential without (center) and with a current drainage system (right). Note the elimination of the anodic shifts after the drainage (right).

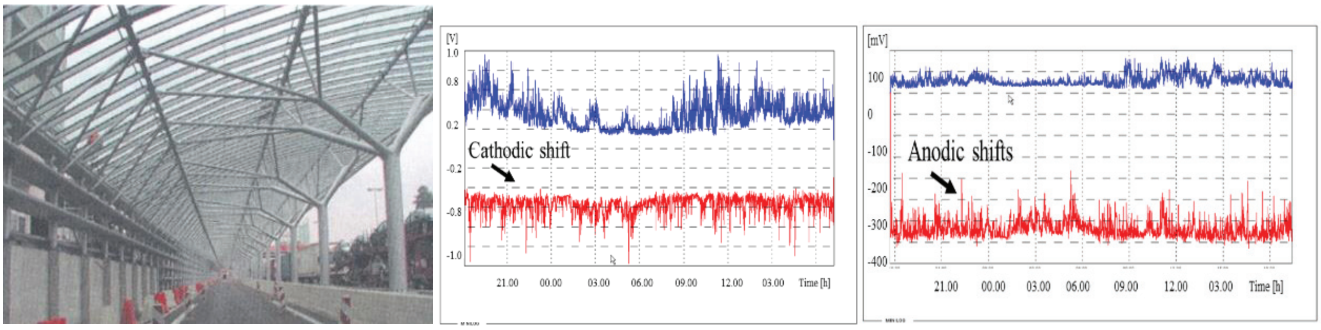

**Figure 4:** Noise barriers. Monitoring of the concrete basement rebars. Cathodic and anodic shifts of the steel rebar electrochemical potential are influenced by stray current (red line) and alternate (blu line) current (center-right).

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## Protection with passive systems

**Buildings:** Passive protection is more conventionally applicable in buildings, where the rebar corrosion is mainly caused by the carbonation reaction. These structures are generally less prone to intense corrosion, particularly advanced forms of localized corrosion caused by chlorides. In structures that do not come directly in contact with detrimental salt-rich solutions, the deterioration is largely controlled by the form, height, orientation, and cyclic exposition degree to the atmospheric agents. The South-west facades are more subjected to carbonation as compared to the Northeast sides. These latter remain more humid and organic growth is often detected. The height of buildings also plays a significant role in the degradation. With the altitude, the structures are more exposed to environmental conditions, such as wind and sun irradiation (Figure 6 left-center). Hydro-demolition with depth may increase the costs and a too high material elimination may influence the static behavior of the structure (Figure 6 right). Depending on the corrosion intensity, the active protection may avoid the complete cleaning of the rebars.

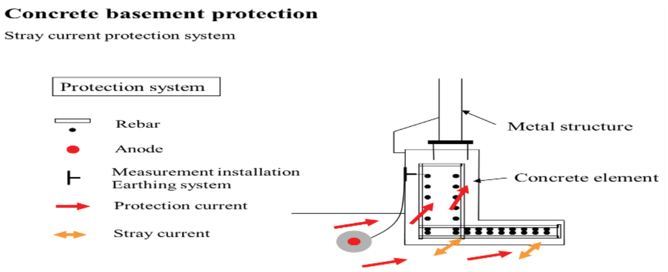

**Figure 5:** Concrete basement active protection concept. The stray currents enter (protection) and exit (corrosion) the infrastructure (orange arrows), while the protection currents enter the structure (red arrows) and are generated by the Titanium anode.

Passive protection implies preparation works, similar to active protection, but no Titanium net is applied. Hydro-demolition at ca. 400 bars is done to get rid of the deteriorated concrete. The rebars are cleaned and roughened and a corrosion protection paint is usually applied (Figure 7 left). Afterward, mortar repopulation and curing are done (Figure 7 left-center). Working defects may both be present in active and passive protection systems. Local reprofilation may remain visible because of the color difference between the new and the old cementitious material and aggregates (Figure 7 center). Aggregate scratches may be a result of dragging during the surface finishing (Figure 7 center-right) or surface irregularities can be clearly seen depending on the sun ray incidence (Figure 7 right).

**Bridges:** Civil engineering infrastructures can also be restored with passive protection techniques. The adhesion strength between the repair mortar, coatings, and the concrete substrate is a main parameter measured during restoration [12]. This can vary from 0.5 to 3.0 Mpa after 28 days (Figure 8 left-center). In active protection systems, the installation of a Titanium net may have an influence on the adhesion, although reduced with appropriate precautions. In aggressive environments, such as tunnels and bridges, an additional physical and optical barrier is often required on the surface. Therefore, elastoplastic multi-layer surface coating, impregnations, or hydrophobic agents are applied (Figure 8 right). This is to avoid or decrease the ingress of aggressive

**Figure 6:** Highly carbonated South façade (left) and concrete spalling along the rebars due to corrosion induced by carbonation at a high level of a building (center). Elimination of the contaminated concrete and exposition of the steel rebars (right).

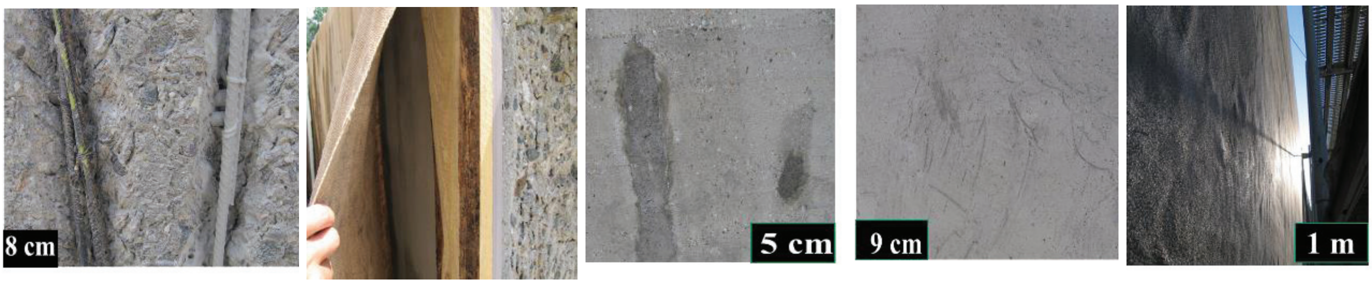

**Figure 7:** Preparation work and damage during the restoration processes. From left to right: sandblasting and cleaning of the steel rebars and application of a protection paint, mortar curing after spaying on the surface, color differences in localized restored points, stone aggregates scratch lines, and uneven surface visible through sun ray reflection.

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**Figure 8:** Multi-layer adhesion strength on a bridge (left), pull-off metallic cylinders with 50 mm diameter (center), and organic coating applied on several layers on the surface restored with mortar (right).

elements. In active protection systems, these precautions appear not necessary.

## Conclusion

The active protection systems are more appropriate for infrastructure with chloride contaminations, where the electrochemical potential measurements can be more easily evaluated, due to localized corrosion phenomena. This is the case for bridges and tunnels. Passive protection is more prone for buildings, where the rebar corrosion is mainly caused by carbonation. Nonetheless, passive restoration is more widely used because of the reduced costs. In this concern, less bulky special anodes made of alternative light materials or fibers may reduce costs and allow more widespread use of full-active protection systems. In fact, the systems allow the corrosion monitoring and protection of the infrastructures with a non-destructive technique. So that it would not be necessary to wait for concrete spalling in order to initiate a restoration process.

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