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TECHNICAL REPORT



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CORROSION MONITORING SYSTEMS
INSTALLED IN PORTUGUESE STRUCTURES

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**CORROSION MONITORING SYSTEMS INSTALLED IN
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NOTE:

The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the data presented.

PREFACE

This Technical Report (TR) is one of a series of technical reports which were prepared inside the DURATINET project working Group WG-A 6 “Smart & green structural materials” concerning new materials or systems which could improve the durability of structures and to reduce the carbon footprint associated to the construction and maintenance of structures.

In this TR results obtained from different corrosion monitoring systems installed in several Portuguese reinforced concrete structures are presented. The examples presented refer to systems in build in new structures and systems specially designed to evaluate the performance of different repair options in existing concrete structures damaged by reinforcement corrosion and which were submitted to repair/rehabilitation.

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1 Introduction

Structural deterioration of reinforced concrete structures affected by corrosion is a gradual process consisting of a few phases during service life, including corrosion initiation, concrete cracking, excessive deflection and final collapse due to loss of structural strength.

The use of permanent monitoring systems to assess the corrosion of ordinary reinforcement in concrete has been recognised as an important tool to prevent premature deterioration of reinforced concrete (RC) structures and to assist the development of reliable models that allow designing durable new structures in aggressive environments and to establish rational maintenance and repair strategies of reinforced concrete structures affected by reinforcement corrosion.

Though it is well known that the selection of parameters to be measured in each particular situation as well as the locals of the structures to be instrumented are critical for the success of each installed system, more advances are still needed, especially in the development of sensors suitable for measuring the selected parameters in existing concrete structures.

The most relevant advances in the development of corrosion monitoring systems have been achieved in the proposal of embedded sensors for application in new structures. For these structures sensors are embedded during concreting and the electrolytic contact between the sensor and the concrete is warranted, being possible, at present, to measure, continuously, the corrosion potential, the corrosion rate, the concrete resistivity and the concrete chloride contents in new structures.

For existing structures sensors have to be fixed after concreting. The electrolytic contact between the original concrete and the sensors is much more difficult to be established in a non-intrusive way and few systems have been proposed, being more advances in this field still needed. Sensors are usually installed inside holes, being the electrolytic contact between the original concrete and the sensor established by pressing the sensor to the concrete or by using sealing materials.

2 Design of the corrosion monitoring systems

The selection of the parameters to be measured in each particular situation as well as the locals of the structures to be instrumented are critical for the success of each installed system.

In the corrosion initiation period, during which the aggressive agents penetrate in the concrete cover until reach the steel, the most relevant parameter in marine environment is the chloride content. In industrial or indoor applications where extensive carbonation could develop; carbonation front and humidity are usually followed.

On the propagation period, during which the rebar corrodes until a maximum tolerable level of damage, corrosion rate has been identified as the most relevant parameter in the corrosion.

If organic inhibitors are applied to the concrete surface, to reduce corrosion, it will be important to know the effectiveness of penetration inside the concrete cover and to obtain information about the corrosion rate of steel in the contaminated concrete.

When surface treatments are used to prevent or reduce the penetration of water, besides the control of evolution of moisture inside concrete, it is also necessary to follow the loss of the protective properties of the surface treatments with time in order to define intervals of repainting that allow an effective control of costs.

The locals of the structure to be instrumented are usually the locals most likely to develop reinforcement corrosion. Thus, selected locals with specific aspects of structural design or construction practices are often chosen (concreting joints and expansion joints, areas of high density of rebars, corner areas, etc.). Also environmental exposure conditions particularly aggressive are the usually selected (areas of condensation in general and tidal and splash zones in marine structures).

Monitoring corrosion systems installed in Portuguese structures are constituted by the following sensors appropriated to be embedded in concrete: galvanic current sensors, corrosion potential sensors, concrete resistivity sensors and thermometers.

In new structures or repaired structures where all the original concrete cover is completely removed, galvanic current sensors are usually used to follow the progress of aggressive agents in concrete like chloride ions or carbonation (Fig. 1). When the despassivation front is detected in the small sections of low carbon steel electrodes embedded in the concrete cover at different depths, addition protection systems could be decided, like the application of protective coatings.

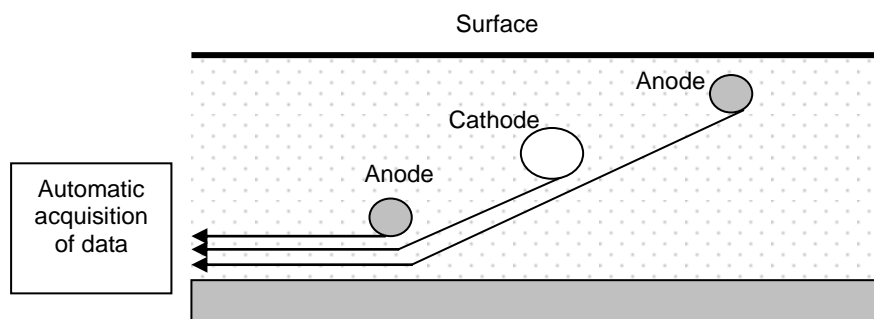


Fig. 1. Anode ladder type galvanic sensor (GS-AL)

Galvanic current sensors have also been installed in existing structures to follow the effect of corrosion inhibitors or coatings. In that case, typically, concrete cores with a small section of rebar surrounded by the contaminated concrete are removed from the structure. The core is instrumented in lab using the steel embedded in concrete as an anode and a stainless steel electrode as the cathode. After instrumentation the galvanic current cell is replaced in the original site, using sealants materials (Fig. 2). Repair materials like corrosion inhibitors or protective coating are then applied on concrete surface. In Fig. 3 the instrumentation of an existing RC structure is illustrated (usually several sensors are installed simultaneously).

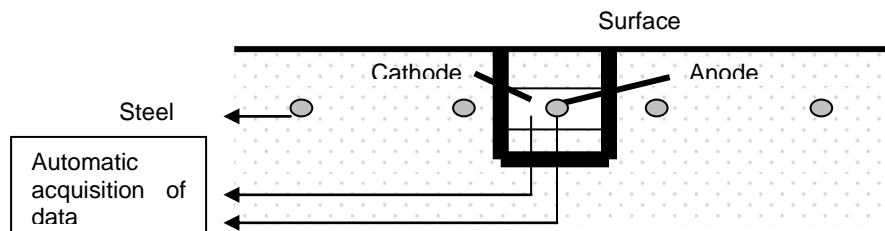


Fig. 2. Core type galvanic sensor (GS-C)



Fig. 3. Example of the instrumentation of an existing RC structure damaged by reinforcement corrosion and submitted to repair works.

In new structures **corrosion potential** is also always measured to detect the beginning of reinforcement corrosion. For the measurement, reference electrodes of MnO₂ are usually installed in different locals. Activated titanium has also been used in some applications. In existing structures reference electrodes are also always installed in holes made wilfully and that are subsequently filled with an appropriate mortar. In areas of the structures already contaminated with aggressive agents, the measurement of corrosion potential can provide information on the influence of repair procedures (removal of contaminated concrete surrounding the reinforcement, application of corrosion inhibitors, application of protective coatings, etc.).

The measurement of electric resistance of concrete can provide important information about the progression of despassivation front, the saturation degree of concrete and the effectiveness of corrosion protection systems and, therefore, **resistivity sensors** are also always installed.

In addition **temperature sensors** are also always installed since this parameter directly influences the corrosion rate of reinforcement and transport properties of aggressive agents in concrete cover.

The acquisition of data is performed with automatic acquisition systems. These systems can send data by phone communication, however periodic maintenance of the systems should be provided in the project. Most of the failures are due to lack of maintenance, especially in the non-replacement of the internal batteries of the acquisition systems.

In the following chapters different corrosion monitoring systems installed in Portuguese reinforced concrete structures are presented Fig. 4. The examples presented refer to systems installed in new structures to prevent the beginning of reinforcement corrosion and systems specially designed to evaluate the performance of different repair options applied in existing concrete structures damaged by reinforcement corrosion.

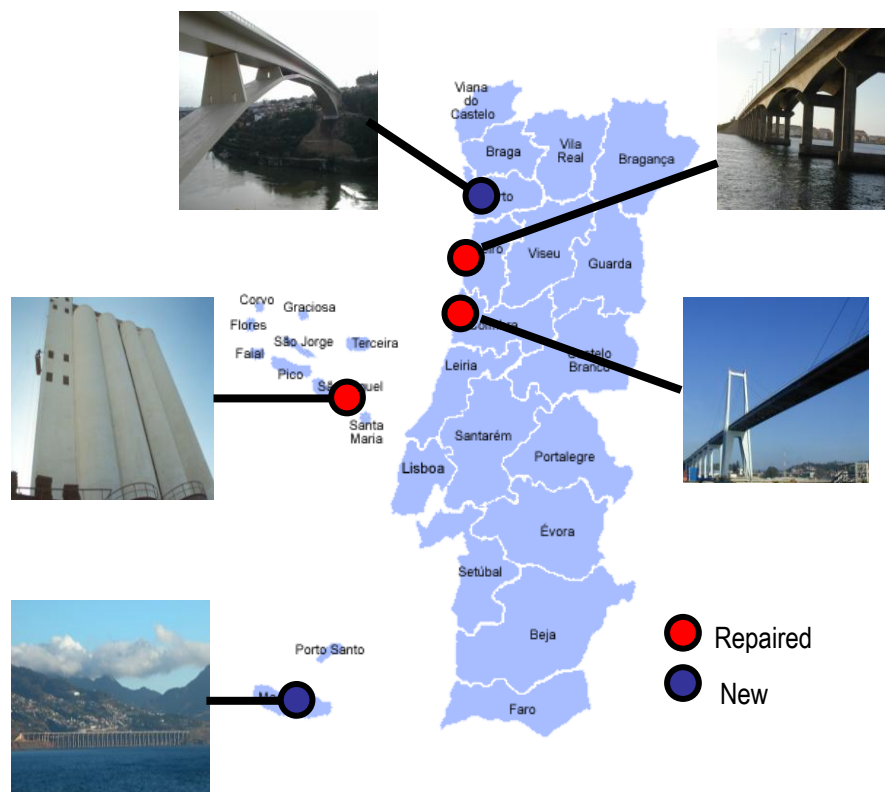
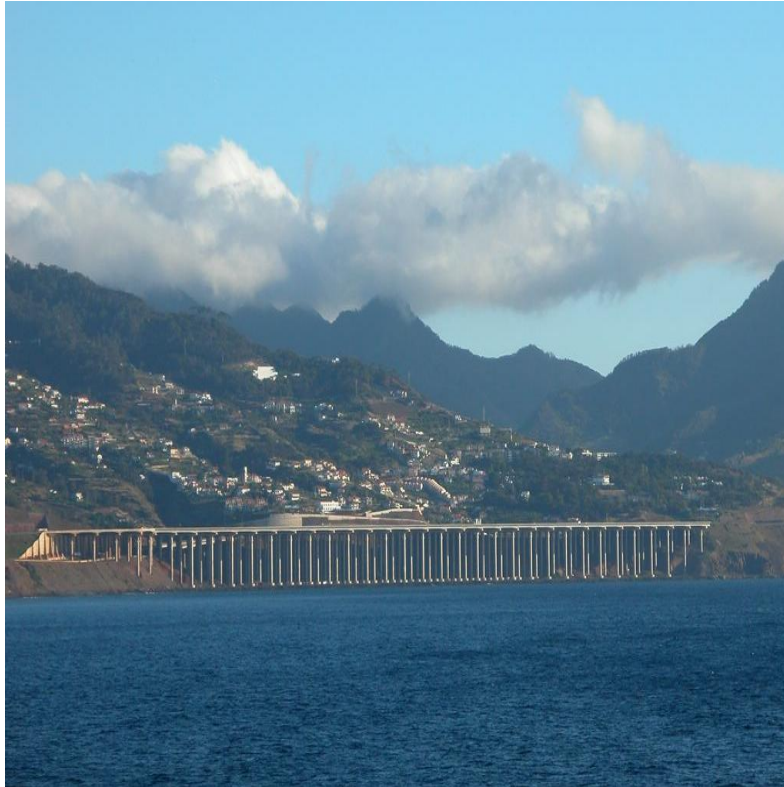


Fig. 4. Location of the structures instrumented.

3 Application in Portuguese Structures

3.1 New structures

3.1.1 Funchal Airport in Madeira Island



Madeira Airport runway was extended by two hundred meters in 1977 after the TAP 727 crash. The length of the former runway of the Madeira Airport was, however, a serious restraint to the development of the island, since only small-medium planes could land. In 2000, it was extended again to a length of 2781 meters. As a result, the runaway became nearly double the length it had been during the 1977 incident.

Because of the local conditions, the solution adopted to extend its length, was to slightly turn the existing runway and to build a bridge, crossing a shallow water bay nearby, 57 meters above the sea level. This new runway extension was built over the ocean. Instead of using landfill to construct the extension, the runway sits on 180 columns that are 70 meters tall. After it was completed, the Madeira Runway extension won the Outstanding Structures Award by the International Association of Bridge and Structural Engineering. This bridge, 1020 metres long x 180 metres wide, was designed to carry the loads of the landing impact of a plane type Boeing 747. Due to the unusually large size of the structure, special care was taken in order to minimise the visual impact of the structural elements.

The structural solution, in reinforced concrete, consists of an array of large portal frames with circular columns and prestressed beams supporting a deck slab bi-directionally prestressed. When possible, direct foundations, through large concrete footings, were adopted. Where the rock formations at surface had no adequate capacity, indirect foundations with concrete piles (reaching depths up to 60 metres) were used.

The huge volume of earthwork generated a surplus quantity of this material, so the area of the bay beneath the structure was reclaimed, which very much facilitated the construction

works. Special care was taken on making the embankment, in order to minimise the impacts on the local environmental conditions.

Purpose of instrumentation

To obtain information about the progress of despassivation front in the concrete cover (carbonation and chlorides ingress) in the Madeira runway extension.

Location of the instrumentation

A monitoring system consisting of corrosion sensors embedded with automatic data acquisition was installed.

Instrumentation was installed in 23 areas. The localization of the areas took into account the influence of differential exposure conditions and specific aspects of structural design or construction practices.

Sensors and measurement equipment

Sensors

In each of the 23 areas the following set of sensors were installed:

Galvanic cell - anode ladders type galvanic sensor (GS-AL).

Resistivity sensors – Two graphite electrode resistivity sensors

Temperature – Pt100 thermometer appropriated to be embedded in concrete

Corrosion potential – ERE-Probe reference electrode from Germann Instruments and activated Ti.

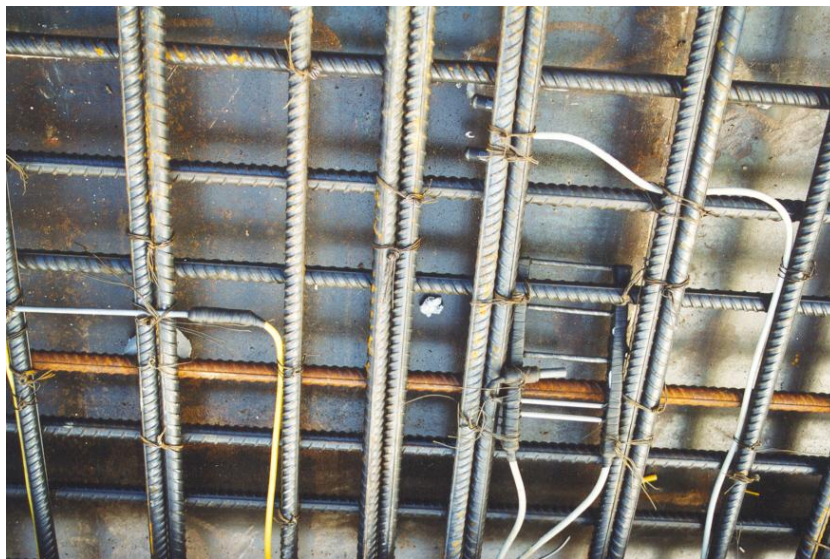


Fig. 5. Sensors before concreting.



Fig. 6. Instrumentation of pier.

Acquisition data equipment

Datataker 500 automatic acquisition data equipments were installed in centralization boxes. Due to extension of the airport, a centralization box was installed in each pier. A single box receives all information from sensors installed in beams and deck slab.



Fig. 7. Centralization box installed next to the airport runway that receives all information from sensors installed in beams and deck slab. Top – during the installation of automatic acquisition of data. Below – ten years after.



Fig. 8. Current appearance of the centralization box installed on a pier.

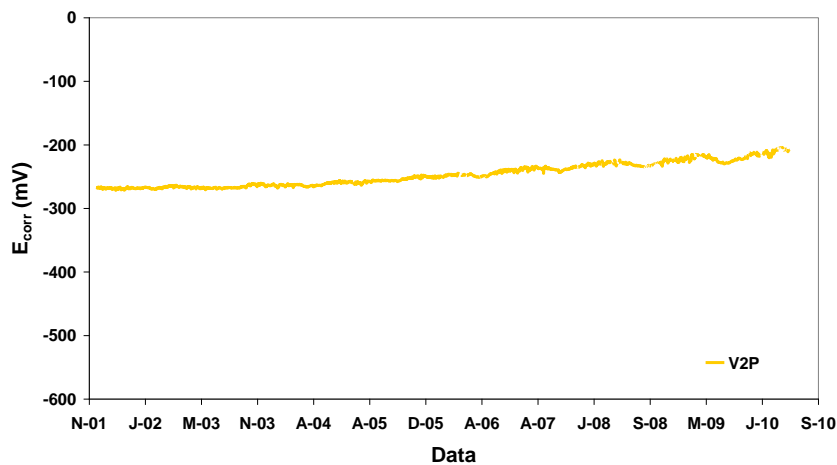
Data management and examples of outcomes

The corrosion monitoring system was installed in 2001 and automatic acquisition of data, with daily periodicity, was provided since then.

Examples of outcomes

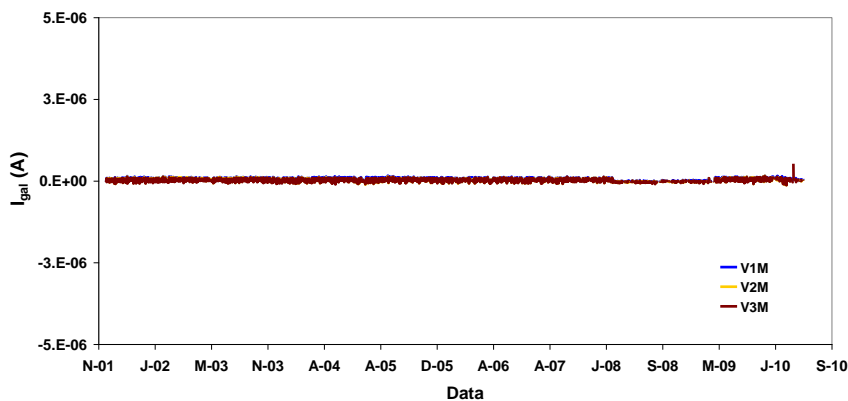
Corrosion potential (Ecorr)

Measurement of Ecorr showed that reinforcement corrosion do not start during the monitoring period.



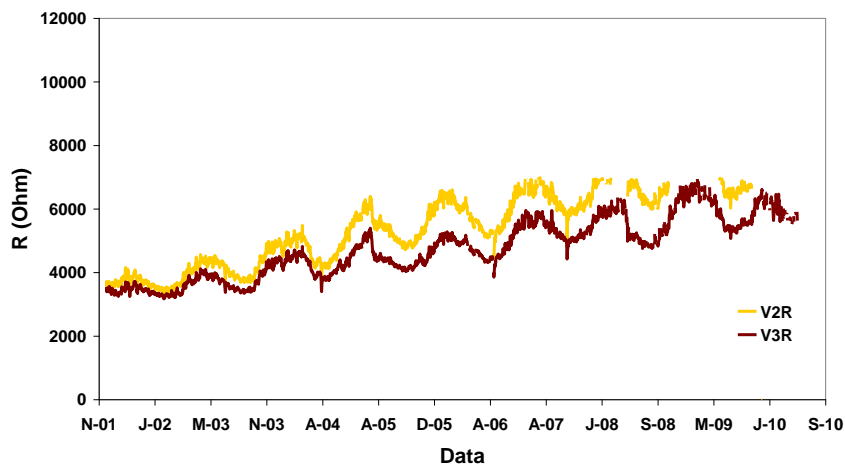
Galvanic Current (I_{gal})

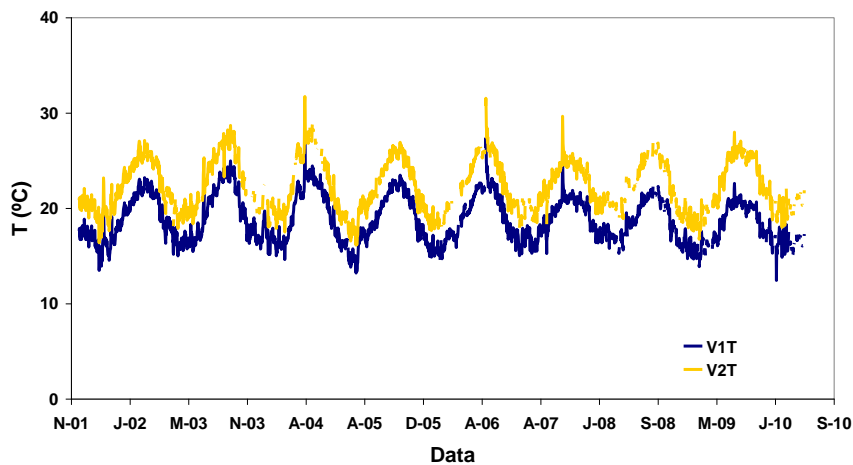
Galvanic currents measured during the monitoring period are low and indicative that the reinforcement is not corroding.



Concrete electrical resistance (R)

No significant changes of R occurred during the monitoring period. R variations have been attributed to the variations of environmental parameters and to the evolution of concrete hydration over time.





3.1.2 Infante D. Henrique Bridge



Infante D. Henrique Bridge, is a concrete bridge 380 m long that crosses the river 70 m above the riverbed. It has a 280 m span and a 20 m wide deck, with two traffic lanes. It consists of an unusually lowered laminar arch, a 280 m span with a 25 m rise contrasting with the considerable rigidity of the deck.

The deck has a box girder section and a constant height of 11 m. It is supported on piers set 35 m apart. The polygonal laminar arch has a constant thickness of 1,5 m and its width varies between 20 m at the abutments and 10 m in the central deck area, which is 70 m long. At the abutment the arc has been lightened to reduce its weight. In this zone the riverbed is approximately 160 m wide.

The construction began on 1999, being the corrosion monitoring system installed during construction.

Purpose of instrumentation

To obtain information about the progress of despassivation front in the concrete cover (carbonation and chlorides ingress).

Location of the instrumentation

A monitoring system consisting of corrosion sensors embedded with automatic data acquisition was installed.

Instrumentation was installed in 23 areas. The localization of the areas took into account the influence of differential exposure conditions and specific aspects of structural design or construction practices.

Sensors and measurement equipment

In each of the 23 areas the following set of sensors were installed:

Sensors

Galvanic cell - anode ladders type galvanic sensor (GS-AL).

Resistivity sensors – Two graphite electrode resistivity sensors

Temperature – Pt100 thermometer appropriated to be embedded in concrete

Corrosion potential – ERE-Probe reference electrode from Germann Instruments and activated Ti.



Fig. 9. Sensors before concreting.

Acquisition data equipment

Information from sensors was wire transferred to two automatic data acquisition systems, model Argilent 34970, powered by electric current of 220 V and installed in a single box of centralization, located inside of the bridge deck. The systems have wireless capability to data transmission.

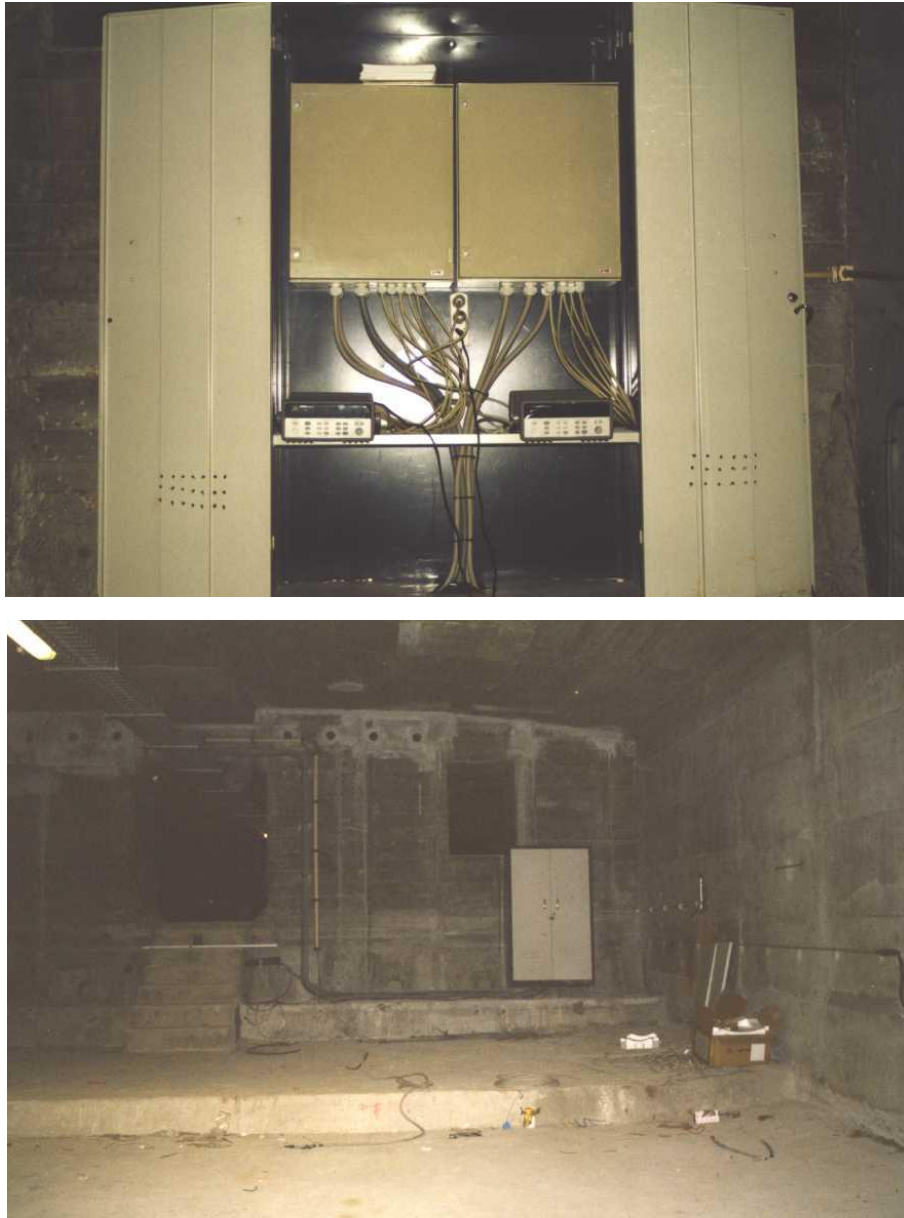


Fig. 10. Aspects of the automatic acquisition systems installed.

Data management and examples of outcomes

Automatic acquisition of data with daily periodicity was provided. The corrosion monitoring system provides corrosion potential, galvanic current, resistivity and temperature variation over time. The results are interpreted by the owner.

3.2 Repaired structures

3.2.1 Barra Bridge at Aveiro



The bridge was designed by the Portuguese bridge designer Prof. Edgar Cardoso, 1971, and started operation in 1975.

The bridge is located on Km 0+824 of E.N.109-7 over Ria de Aveiro near the Atlantic sea. It is totally made of reinforced concrete and has a 578.00 meter length, between the support axes on the abutments. The central span has 80,00 m and the access viaducts, symmetric as refers to the central span, have 249,00 m, each being formed by an extreme span of 25,00 m and seven spans of 32,00 m. The deck of the viaducts consists of a 16,60 m wide beam-T slab with 4 longitudinal beams of constant thickness and equal to 0,40 m. The beams, of variable height, between 1,30 metres in the span and 2,00 metres on the supports, are longitudinally pre-stressed. The slab has a variable thickness between 0,18 m and 0,25 m and is cross-sectionally pre-stressed. There are partial transversal beams on the supports, each involving just two beams, as well as reinforcements in the “swallow tail” bottom flanges with 5,00 metres on each side of the pier axis.

The bridge was submitted to several rehabilitation works and areas with reinforcement corrosion, due to chloride penetration and carbonation, were also repaired. The corrosion monitoring system was installed in 2008 during the rehabilitation works.

Repair procedure

The repair procedure of defects related with reinforcement corrosion comprises:

- the removal of delaminated concrete in the area beyond the reinforcement;

- replacement or strengthening of the corroded reinforcement;
- replacement of concrete cover, followed by the application of a migrating corrosion inhibitor and a coating system.

Purpose of monitoring system

A monitoring system, consisting of arrays embedded corrosion sensors with several automatic data acquisition units was installed.

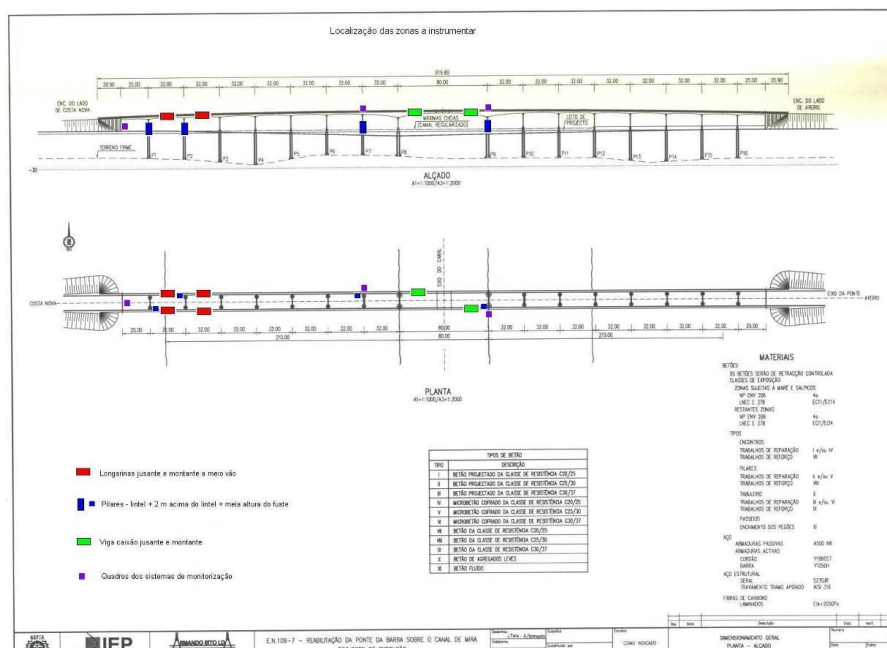
In areas without concrete cover removal the installation of the corrosion monitoring system aims to obtain information about the effect of migrating corrosion inhibitor and coating system application on the progress of reinforcement corrosion.

In areas with complete concrete removal the installation aims to obtain information about the progress of despassivation front in the concrete cover (carbonation and chlorides ingress).

Interface zones between areas with removal and no removal of concrete were also instrument to follow the possible occurrence of corrosion due to cracking in the interface of the hardened concrete and the new concrete.

Location of the instrumentation

Sensors were installed in eighteen areas. The localization of the areas took into account the influence of the different exposure conditions, the need to collect data on the effectiveness of the repair method used and to ensure the representativeness of the information collected by the monitoring system.



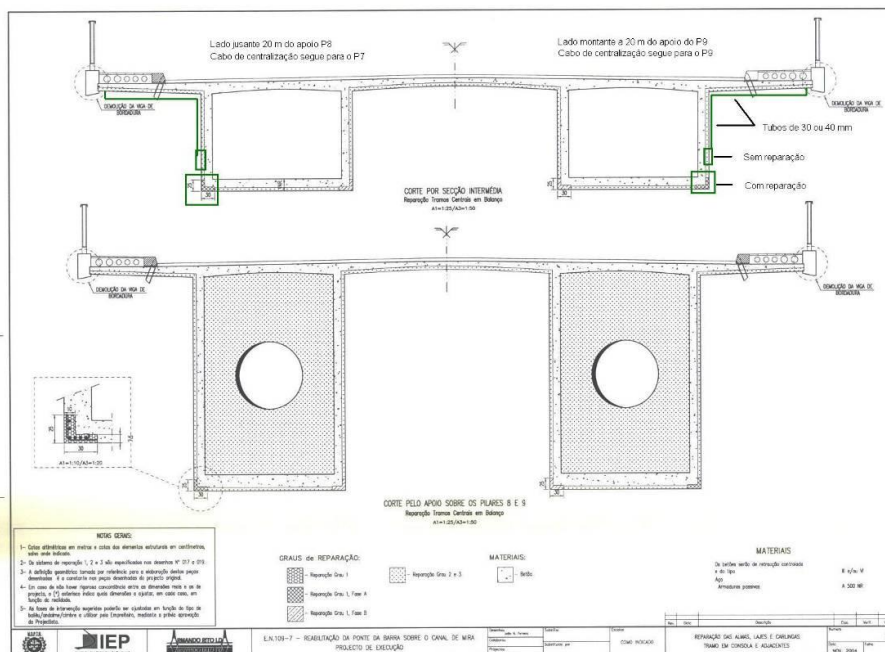
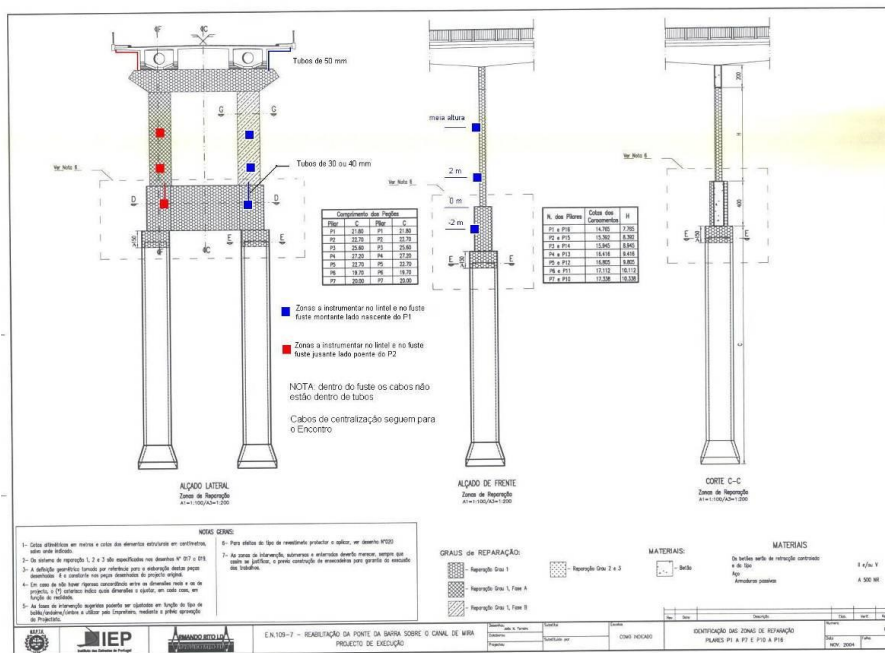


Fig. 11. Locals selected for be instrumented are marked with colour

Sensors and measurement equipment

In each area three zones were instrumented – zones without concrete cover removal, zones with complete concrete removal and the Interface between the two.

Sensors installed

Galvanic cell - In areas with complete removal of concrete cover an anode ladder type galvanic sensor was installed (GS-AL). In areas without concrete removal a core galvanic current sensor was installed (GS-C).

Resistivity sensors – Two graphite electrode resistivity sensors were used in the instrumentation of repaired and no repaired areas. In areas without concrete removal, a core was removed and instrumented with a resistivity sensor in order to preserve the concrete cover and to follow the influence of corrosion inhibitor applied on concrete surface as well as the coating performance over time.

Temperature – Pt100 thermometer appropriated to be embedded in concrete

Corrosion potential – ERE-Probe reference electrode from Germann Instruments and activated Ti. Reference electrodes were installed in areas with complete removal of concrete cover, in areas without concrete removal and in the interfacial zone between the two.

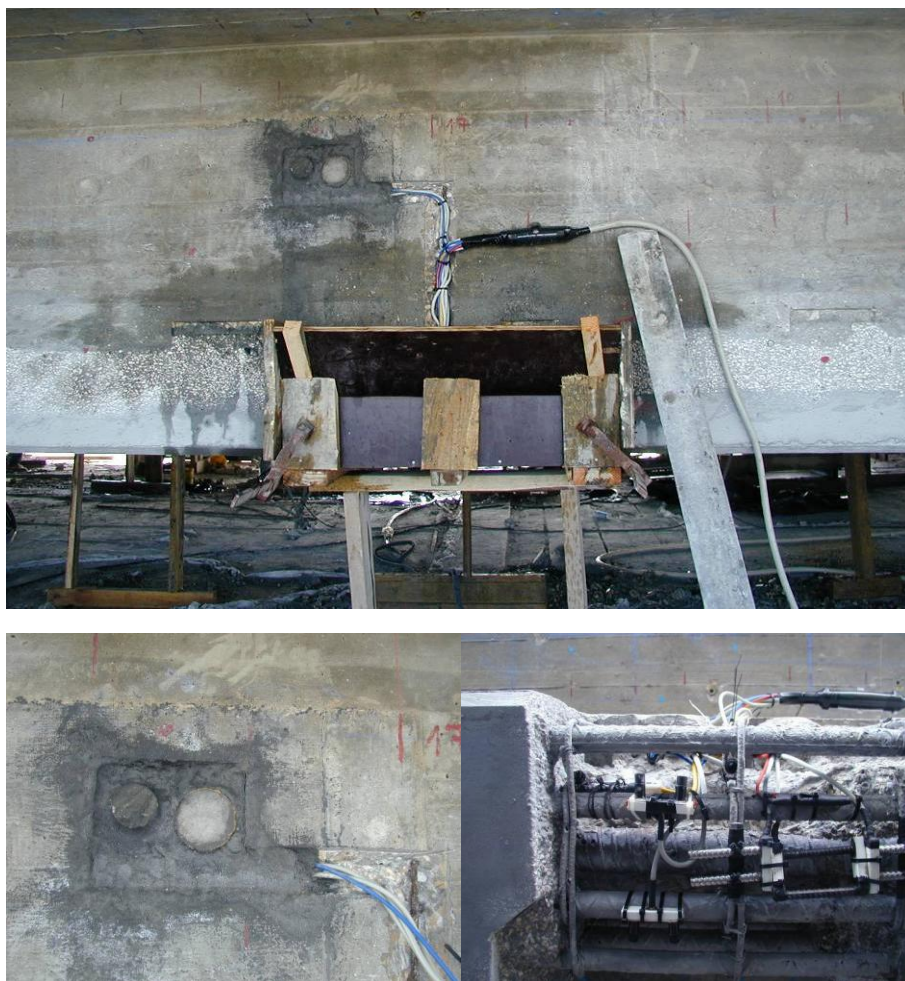


Fig. 12. Aspects of the three types of instrumented areas before concreting: areas with complete removal of concrete cover, areas without concrete removal and the interfacial zone between the two. In areas without concrete removal two cores instrumented are fixed, one with a resistivity sensor and one with a galvanic current sensor. A reference electrode was installed in the interfacial zone.

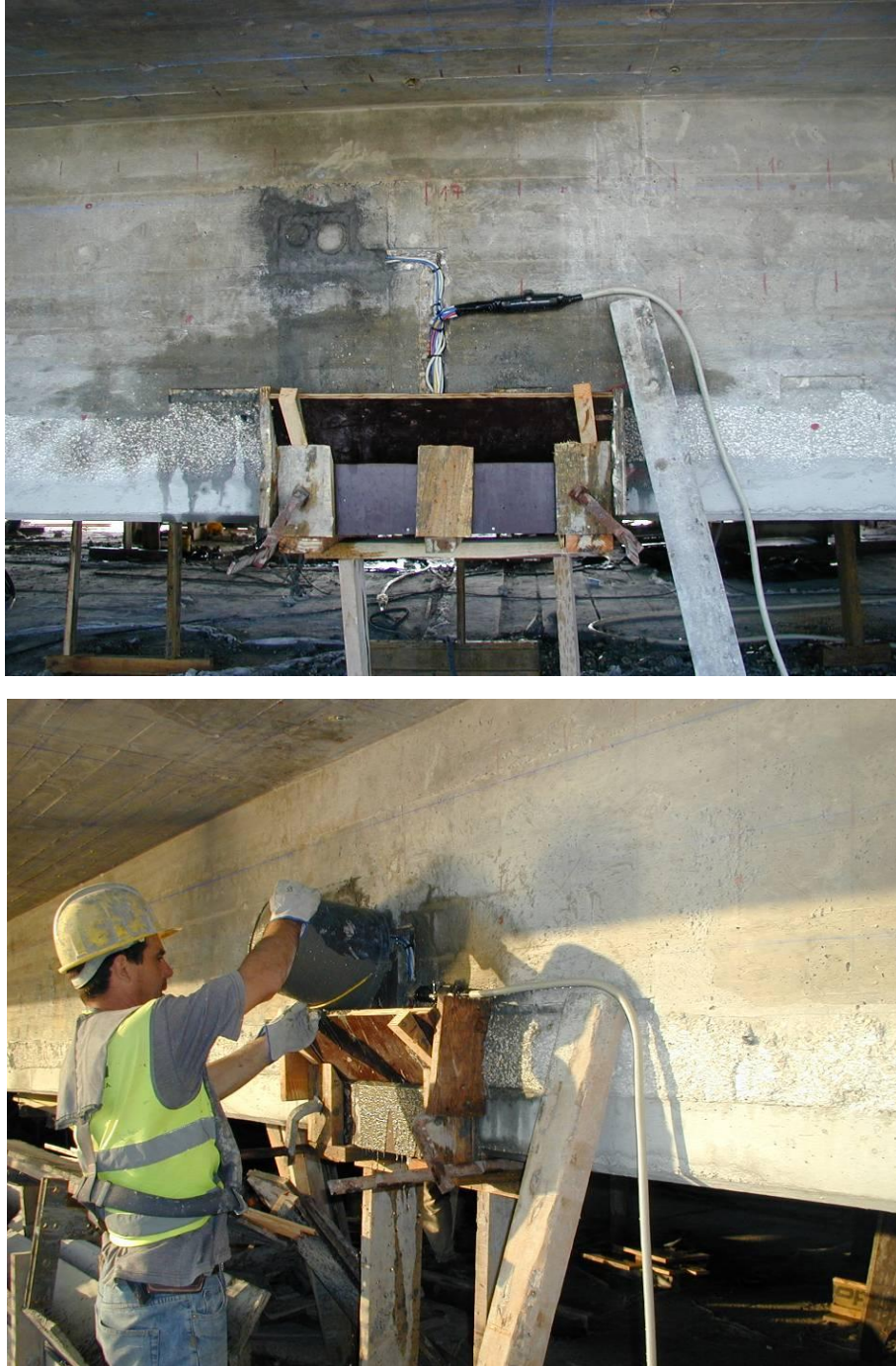


Fig. 13. Aspects of the reposition of concrete cover after the instrumentation in a zone where the removal of concrete was only localized.



Fig. 14. Aspects of the reposition of concrete cover after the instrumentation in a zone were all the concrete cover was removed.

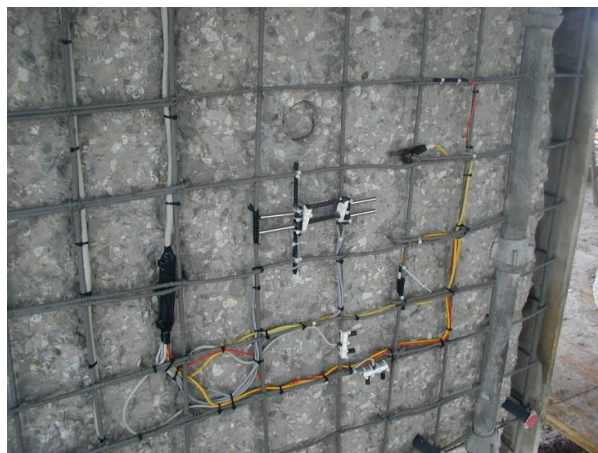


Fig. 15. Instrumentation of an area where extensive removal of concrete took place.



Fig.16. Cables from the sensors were conducted through external pipes to centralization boxes where the systems of data acquisition were installed.

Small slabs were also instrumented with the same sensors to follow the performance of the repair materials, in lab, in accelerated conditions.



Fig.17. Concrete slab with sensors installed for lab tests.

Acquisition data equipment

Datataker 500 automatic acquisition data equipments were installed in centralization boxes. Due to the fact that the boxes were installed in a zone with public access, the boxes were protected by steel cages. The systems have wireless capability for data transmission.



Fig. 18.Aspects of the automatic acquisition systems.

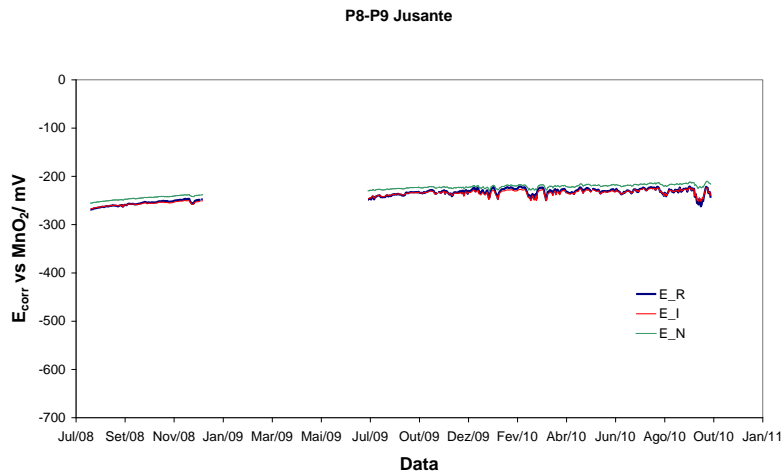
Data management and examples of outcomes

Automatic acquisition of data with daily periodicity was provided. Systems for automatic data acquisition were electrically powered by 220 V current and also with internal batteries capable of powering the systems for a few days. However, during the monitoring period occurred several long electrical failures that caused the loss of data during some periods.

Examples of outcomes

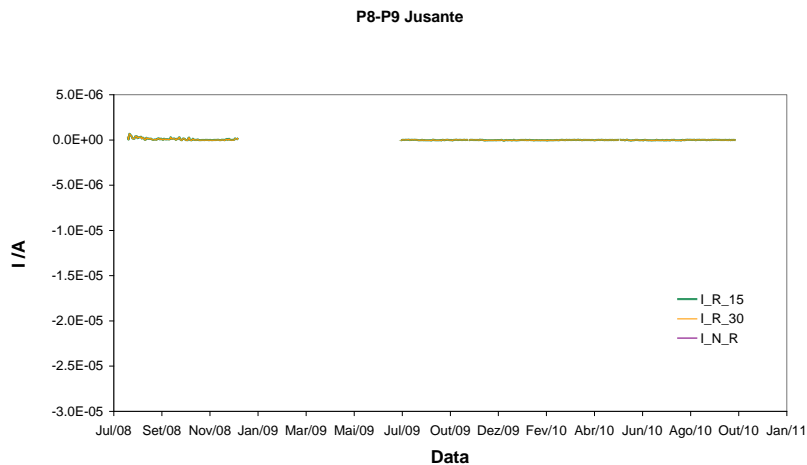
Corrosion potential (E_{corr})

Measurements of E_{corr} showed that reinforcement corrosion do not start during the monitoring period.



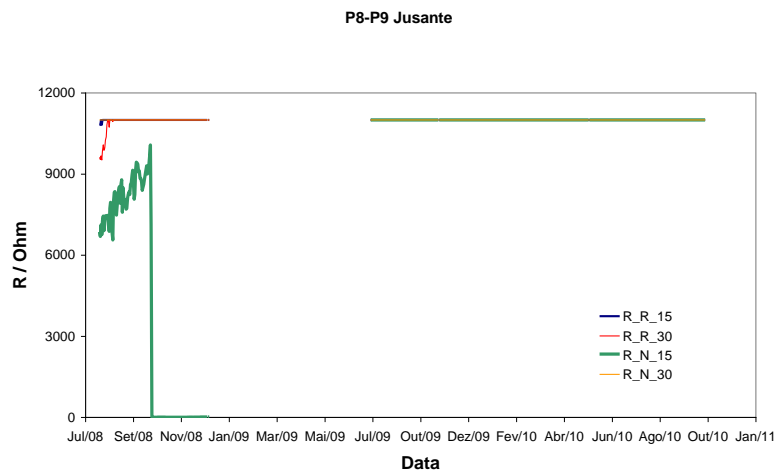
Galvanic Current (I_{gal})

Galvanic currents measured during the monitoring period are low and indicative that the reinforcement is not corroding.



Concrete electrical resistance (R)

In the majority of the instrumented zones no significant changes of R occurred during the monitoring period and R variations have been attributed to the variations of environmental parameters. However in some places a sharp decrease of R values was detected and attributed to the formation of cracks in the concrete cover.



3.2.2 Edgar Cardoso Bridge



Description of structure

Edgar Cardoso Bridge over the River Mondego, also known as Figueira da Foz Bridge, was designed by Portuguese engineer Edgar Cardoso and was inaugurated in 1982.

The bridge is located on Figueira da Foz, in coastline central Portugal and was subjected to a general rehabilitation during two years, which was given by completed on July 28 of 2005.

Edgar Cardoso Bridge includes a 405 m long cable stayed bridge with a steel deck and a main span of 225 m and two prestressed concrete approach viaducts with 45 m spans and a total length of 905 m.

The cable stayed bridge has a central span of 225 m and lateral spans of 90 m. The 85 m above the water level masts include four hollow concrete inclined elements. The stays, spaced 30 m at the deck, are made of galvanized wires passing through saddles at the top of the masts. The deck is a steel construction with two main beams, where the cable stays are fixed (each one made of two 2 m high I beams) interconnected by transverse beams spaced 10 m. These transverse beams support longitudinal girders spaced 8,20 m which in turn support a reinforced concrete slab with a variable thickness of 0,13 m to 0,20 m.

The deck of the approach viaducts have a slab 0,18 m (span) to 0,22 m (over the girders) thick supported by 4 longitudinal beams, spaced 5,20 m with 45 m spans. The prestressed concrete girders have a section of 0,40 m x 2 m at mid span and 0,60 m x 2,50 m at the supports. The slab is prestressed in the transverse beams of the columns by dowels and plumb bearings. Only in the transition pier to the cable stayed bridge the support of the deck allows relative horizontal movements. The longitudinal beams are also interconnected by transverse beams spaced 15 m. Each support alignment has 2 hollow rectangular columns 3 m x 1,60 m connected at the top by a hollow rectangular beam 4,00 m x 1,60 m, with a thickness of 0,25 m. The abutments are apparent. The deck is fixed to the abutment.

A detailed inspection showed that:

- The quality of execution was low. Concreting defects such as voids in prestressed concrete beams and low reinforcement cover were frequent. The painting of the steel structures was also of poor quality.
- Due to the quality of the concrete and to the defective execution, reinforcement corrosion represented a significant anomaly.
- Locally alkalis silica reactions and sulphate attack were identified (mainly in the foundations of the tower).
- In the approach viaducts the prestressed longitudinal girders were not conceived to avoid cracking in service conditions and cracks of 0,2-0,3 mm were frequent.
- In the cable stayed bridge there is a permanent tensile reaction at the transition piers, requiring a redundancy of the anchorage system for safety and reliability.
- The seismic design did not guarantee the seismic resistance required by the new codes and for the approach viaducts the decks were fixed to the abutments, generating considerable seismic forces.

The rehabilitation included the strengthening of the towers and the replacement of the anchorage system of the deck of the cable stayed bridge to the transition piers. The rehabilitation of the approach viaducts included the strengthening of the deck main girders by external prestressing and the introduction of new dissipating devices between the deck and the abutments. The general rehabilitation also includes local repairing and new surface protection of steel and concrete elements.

The bridge was submitted to several rehabilitation works and areas with reinforcement corrosion, due to chloride penetration and carbonation, were also repaired. The corrosion monitoring system was installed during the rehabilitation works.

Rehabilitation procedure

General rehabilitation of concrete structures included local concrete replacement and concrete surface protection. When local repairing involved a thickness greater than 6 cm, micro concrete was used (obtained from a mixture of 70% of per packed grout with 30% of weight of 9 mm aggregates). The rehabilitation procedure of defects related with reinforcement corrosion comprises:

- the removal of delaminated concrete in the area beyond the reinforcement;
- replacement or strengthening of the corroded reinforcement;
- replacement of concrete cover, followed by the application of a migrating corrosion inhibitor and a coating system.

Purpose of instrumentation

In areas without concrete cover removal the installation of the corrosion monitoring system aims to obtain information about the effect of migrating corrosion inhibitor and coating system in the progress of reinforcement corrosion.

In areas with complete concrete removal the installation aims to obtain information about the progress of despassivation front in the concrete cover (carbonation and chlorides ingress).

Interface zones between areas with removal and no removal of concrete were also instrument to follow the possible occurrence of corrosion due to cracking in junction of original concrete and repair material.

Location of the sensors

A monitoring system, consisting of corrosion sensors embedded in concrete, was installed with automatic data acquisition.

Arrays of embedded sensors were installed in 33 areas. The localization of the areas took into account the influence of differential exposure conditions, the need to collect data on the effectiveness of the repair method used and ensure the representativeness of the information collected by the system.

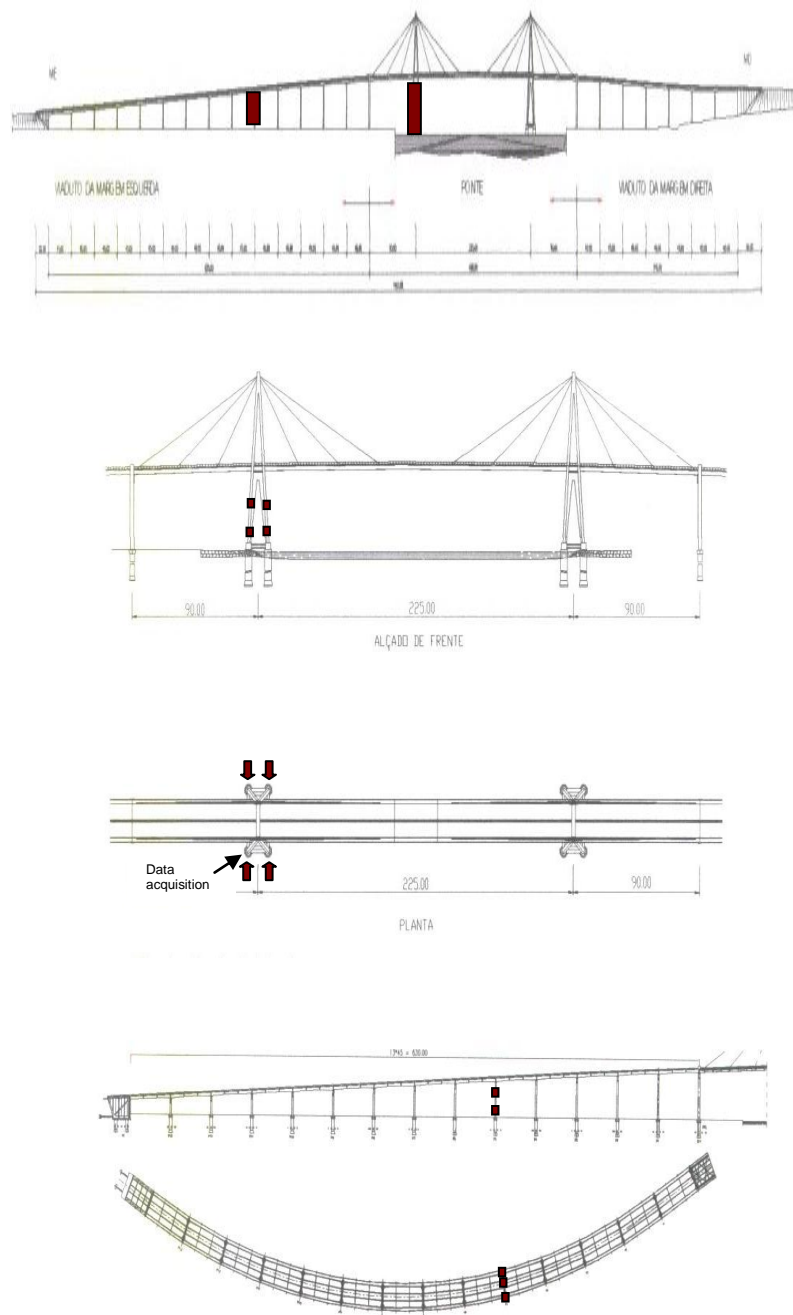


Fig. 19. Locals selected for be instrumented are marked with colour

Sensors and measurement equipment

Sensors

Galvanic cell - In areas with complete removal of concrete cover anode ladder type galvanic sensor was installed (GS-AL). In areas without concrete removal a core galvanic current sensor was installed (GS-C).

Resistivity sensors – Two graphite electrode resistivity sensors was used in the instrumentation of repair and no repair areas. In areas without concrete removal, a core was removed and instrumented with a resistivity sensor in order to preserve the concrete cover and to follow the influence of corrosion inhibitor applied on concrete surface as well as the coating performance over time.

Temperature – Pt100 thermometer appropriated to be embedded in concrete

Corrosion potential – ERE-Probe reference electrode from Germann Instruments and activated Ti. Reference electrodes were installed in areas with complete removal of concrete cover, in areas without concrete removal and in the interfacial zone between the two.



Fig. 20. Instrumentation of an area with complete removal of concrete cover.



Fig. 21. Instrumentation of an area without removal of concrete cover.



Fig. 22. Detailed aspects of the installation of sensors. In areas without concrete removal one cores instrumented with a resistivity sensor was fixed. A reference electrode was installed in the interfacial zone between area with complete removal of concrete cover and areas where the concrete was not removed

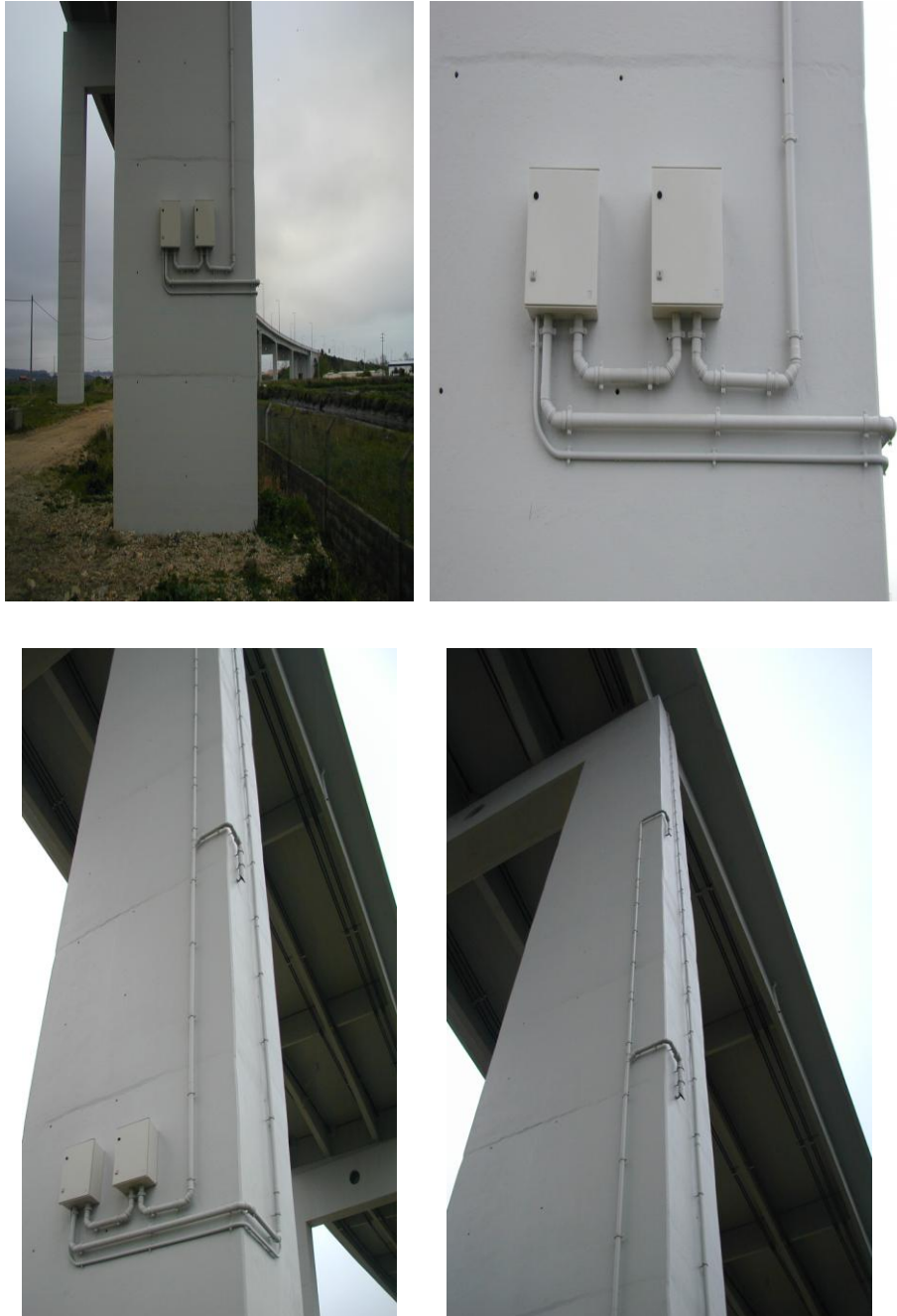


Fig. 23. Cables from the instrumented areas were conducted through external pipes to data acquisition systems installed in polyethylene centralization boxes.

Acquisition data equipment

Datataker 500 automatic acquisition data equipments were installed in centralization boxes. The systems have wireless capability for data transmission.



Fig. 24. Aspects of the automatic data acquisition systems installed inside the bridge.

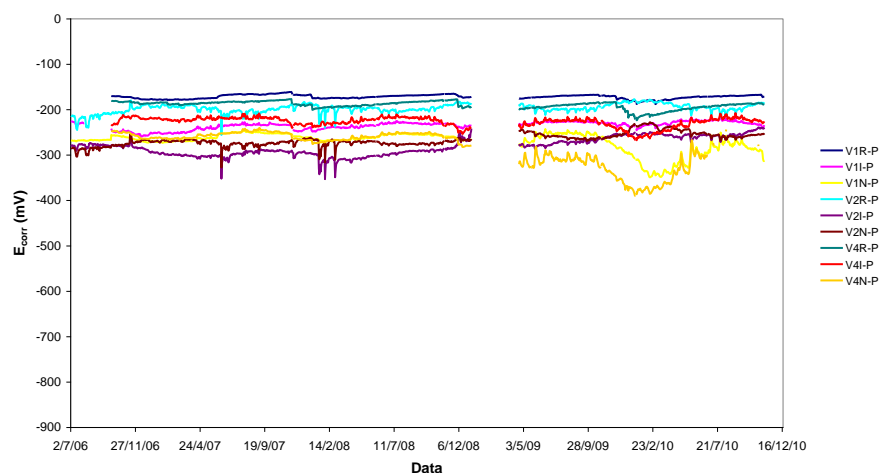
Data management and examples of outcomes

Automatic acquisition of data with daily periodicity was provided.

Examples of outcomes

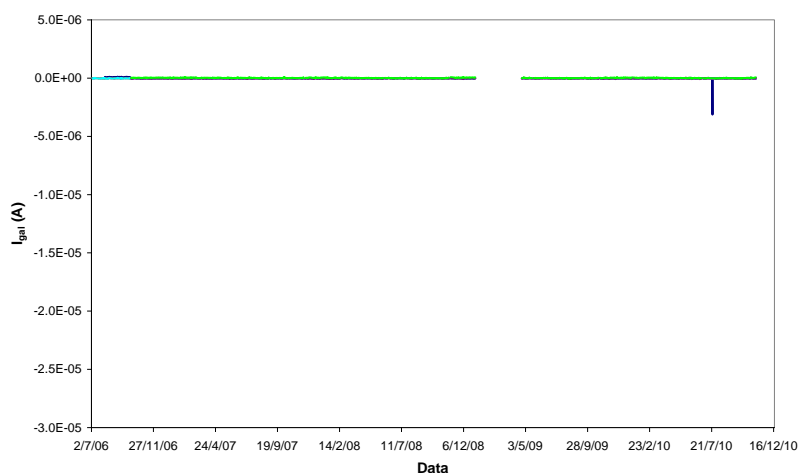
Corrosion potential (E_{corr})

Measurement of E_{corr} showed that reinforcement corrosion do not re-start during the monitoring period.



Galvanic Current (I_{gal})

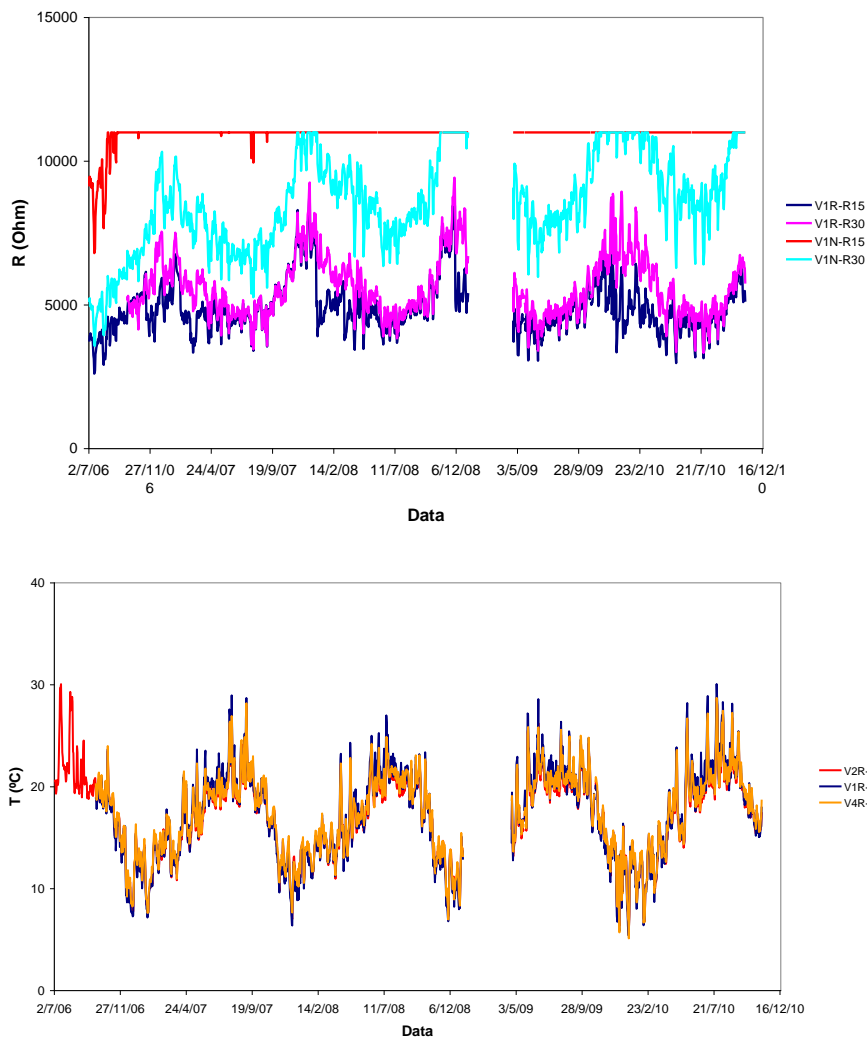
Galvanic currents measured during the monitoring period present low values, indicative that the reinforcement is not corroding.



Concrete electrical resistance (R)

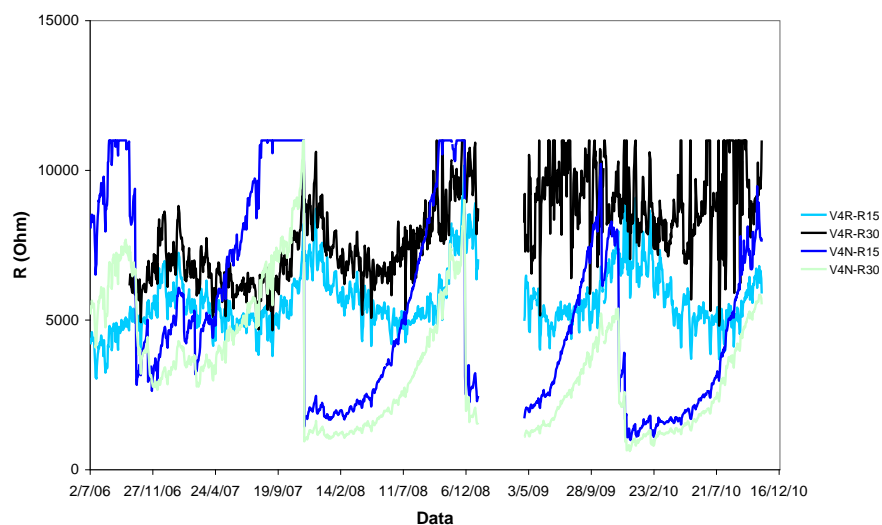
Repaired areas

No significant changes of R occurred during the monitoring period. R cyclic variations have been attributed to the variations of environmental parameters, namely temperature, like it can be seen by comparing of the two next figures.



No repaired areas

Very low R values are measured in one area at 15 and 30 cm of concrete cover (V4N-R-15 and V4N-R30). The values decrease rapidly in certain periods what is consistent with the occurrence of rain followed by a drying period. This behaviour, probably due to cracking, showed that, in this local, the reinforcement is not adequately protected against corrosion.



3.2.3 Silo for cereals



Description of structure

The silo, in reinforced concrete was built in the seventies and presented for long time cracking and delamination of concrete cover due to reinforcement corrosion. Since its construction until the rehabilitation the structure has undergone other three maintenance works: in 1986, 1992 and 1994.

The silo is located at Azores Island, near the sea, under the direct influence of strong sea winds. It consists of a battery of 12 cylindrical cells with inner diameter of 6.5 m and 50 m high, arranged in three rows of four cells, and a tower for equipment installation with maximum height of 62 m.

The concrete presents high porosity and the concrete cover is very variable. The carbonation front has reached in many cases the reinforcement and the chloride content near the reinforcement is high, over the threshold value

Repair procedure

The repair procedure comprises:

- the removal of delaminated concrete in the area beyond the reinforcement;
- replacement or strengthening of the corroded reinforcement;

- replacement of concrete cover with shotcrete, followed by the application of a migrating corrosion inhibitor and a coating system.

Purpose of instrumentation

In the areas where concrete cover was not removed, the installation of the corrosion monitoring system aims to obtain information about the effect of migrating corrosion inhibitor and coating system to decrease the progress of reinforcement corrosion.

In the areas where the concrete cover was removed, the installation aims to obtain information about the progress of the despassivation front in the concrete cover (carbonation and chlorides ingress).

Sensors and measurement equipment

Location of the instrumentation

A monitoring system consisting of different corrosion sensors embedded in the concrete with an automatic data acquisition was installed.

Sensors were installed in eight areas. The localization of the areas took into account the influence of different exposure conditions, the need to collect data on the effectiveness of the repair method used and to ensure the representativeness of the information collected by the monitoring system.

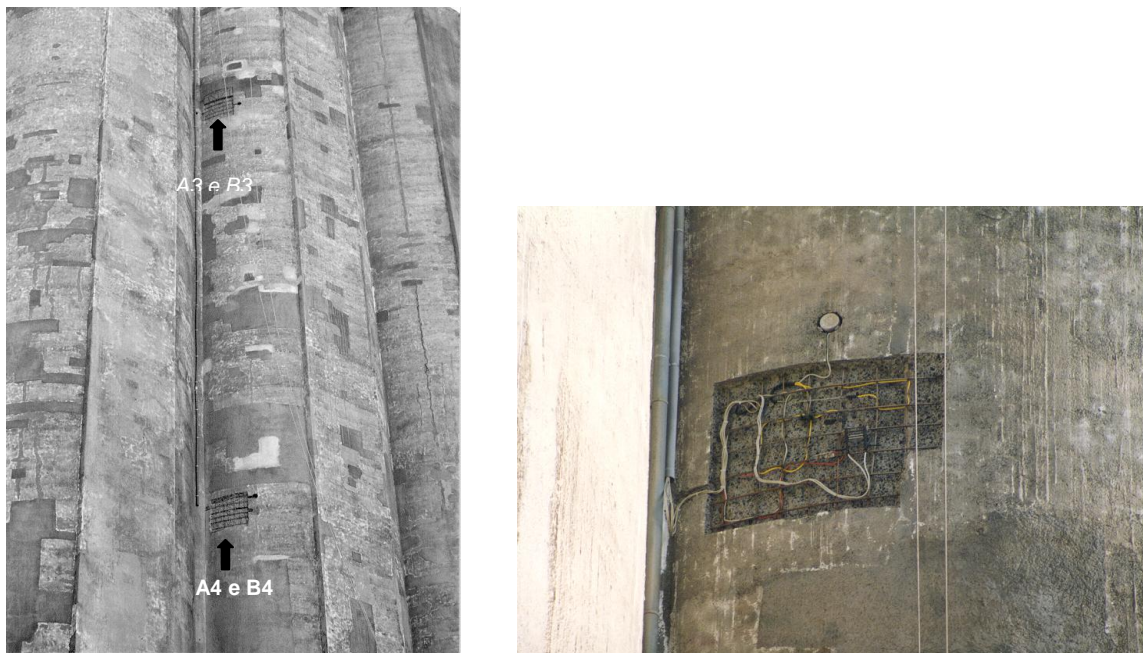


Fig. 25. Locals selected for be instrumented

In the set of cells facing west four areas were selected:

- Two areas at 10 m from the top of the silo - a area with complete removal and replacement of concrete cover and an area where the original concrete cover was not removed;
- Two areas at 25 m from the top of the silo - a area with complete removal and replacement of concrete cover and an area where the original concrete cover was not removed;

Overall cell facing south, four areas in the central cell were selected, using the same criterion:

- Two areas at 10 m from the top of the silo - a area with complete removal and replacement of concrete cover and an area where the original concrete cover was not removed;
- The two areas at 26 m from the top of the silo - a area with complete removal and replacement of concrete cover and an area where the original concrete cover was not removed.

Sensors

Galvanic cell - In areas with complete removal of concrete cover anode ladder type galvanic sensor was installed (GS-AL). In areas without concrete removal a core galvanic current sensor is installed (GS-C).

Resistivity sensors – Two graphite electrode resistivity sensors was used.

Temperature – Pt100 thermometer appropriated to be embedded in concrete

Corrosion potential – ERE-Probe reference electrode from Germann Instruments

Acquisition data equipment

An Argilent datalogger 34970A was installed in the engine room in the top of the silo. The system has wireless capability to data transmission.



Fig. 25. Acquisition data equipment

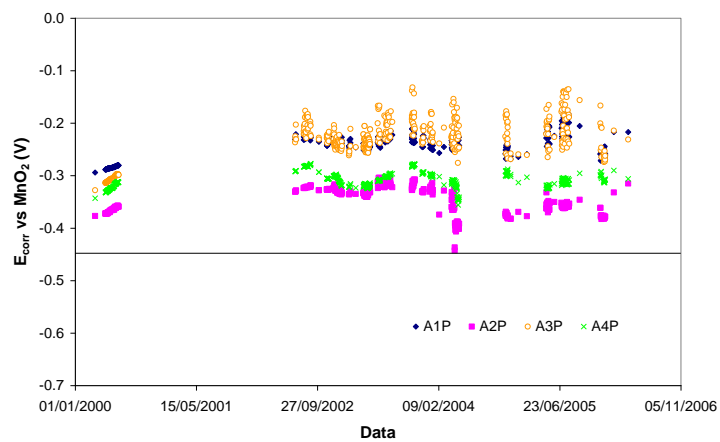
Data management and examples of outcomes

Automatic acquisition of data with daily periodicity was provided. Results were collected during around 7 years.

Examples of outcomes

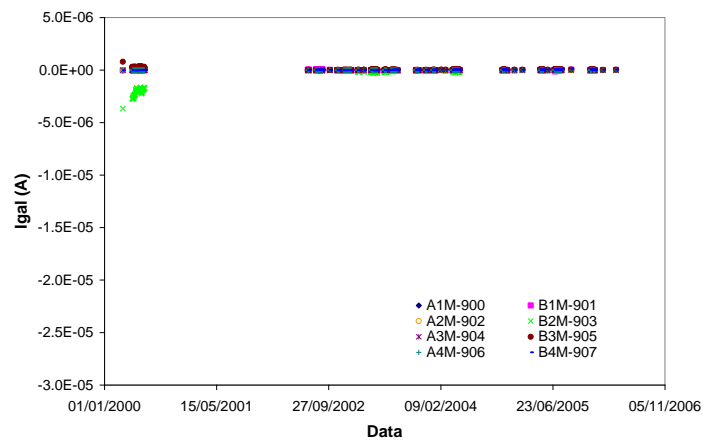
Corrosion potential (E_{corr})

Measurement of E_{corr} showed that reinforcement corrosion do not start during the monitoring period.



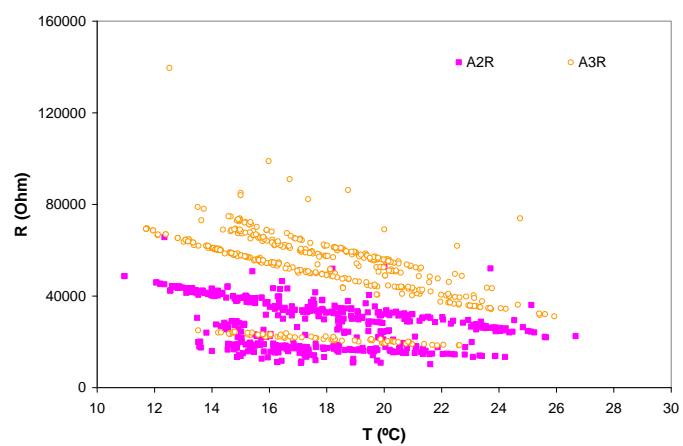
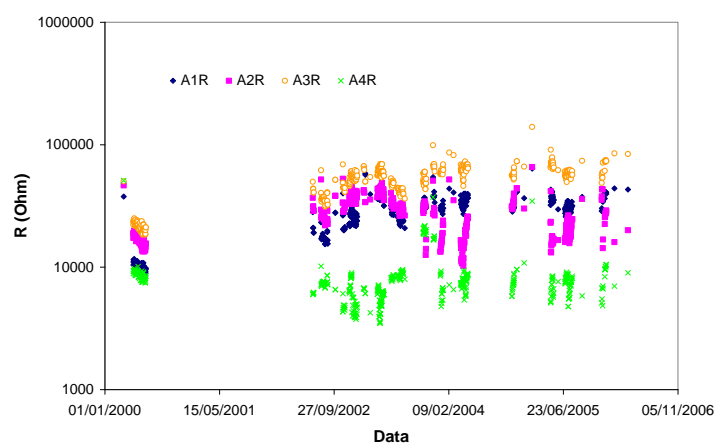
Galvanic Current (I_{gal})

Galvanic currents measured during the monitoring period are low and indicative that the reinforcement is not corroding.



Concrete electrical resistance (R)

No significant changes of R occurred during the monitoring period. R variations have been attributed to the variations of environmental parameters



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