Corrosion prevention of steel frames on an iconic villa by zinc galvanic anode

Xavier Hallopeau[1], Olivier Lesieutre[2], Elisabeth Marie-Victoire[3], Myriam Bouichou [3]

[1]SECCO Corrosion Consulting, 78140 Vélizy-Villacoublay, France
[2]Résilience & Maintenance du Béton, 69250 Fleurieu sur Saône, France
[3]Laboratoire de Recherche des Monuments Historiques, Centre de Recherche sur la Conservation (CRC-USR 3224), Muséum national d'Histoire naturelle, CNRS, Sorbonne Universités, 29 Rue de Paris, 77420, Champs-sur-Marne, France

Abstract. The renovation of a French building classified as an historic monument must meet specific requirements, in particular very precise rules within the framework of the scientific and technical control. The Villa Ephrussi de Rothschild, one of the most beautiful Renaissance-style palaces on the Côte d'Azur, was built on a summit of the St Jean Cap Ferrat peninsula between 1905 and 1912. During the restoration of the east and north facades, it was discovered that the corners of the monumental staircase were covered with an I-shaped metal frame made up of riveted angles and plates. Its advanced state of deterioration made it necessary to reconsider the initial maintenance strategy. In this context, this article discusses the results of its implementation through the partial application of an epoxy coating on the steel frame structure and to the installation of long zinc sacrificial anodes for cathodic protection.

1 Introduction

1.1 Purpose

The villa, named after its builder, Baroness Beatrice Ephrussi de Rothschild (1864-1934) and also nicknamed "Villa Île-de-France", is located on the peninsula of Saint-Jean-Cap-Ferrat, between Nice and Monaco, and offers an extraordinary view of the Mediterranean. An accomplished collector and garden enthusiast as presented in Figure 1, the baroness built this residence in the neo-Italian Renaissance style between 1907 and 1919.

Fig. 1. South façade on the garden of the villa Ephrussi de Rothschild

1.2 Preliminary diagnosis

The villa consists of a metallic structure (beams and floors, with metal I-sections) associated with a masonry of hollow brick rubble. The cladding is covered with coatings and moulded and armored decorations.

These claddings are currently coated with pink paint, while the decorations are coated with white paint. The moulded and armored decors have numerous cracks and are scattered on all facades of the building. The reinforcement is apparent, and the loss of plaster mortar can be significant.

The moulded decoration consists of a body of plaster in grey to dark brown mortar, with variable aggregate content, covered with a finishing layer of yellow mortar, whose thickness varies from a few millimeters to several centimeters. The reinforcements are also of variable dimensions and are mainly located in the mortar of the rendering body (also called "support" mortar), and sometimes also in the finishing layer, especially for fine decorations. Finally, it should be noted that a white mortar is sometimes used as support mortar.

The depths of carbonation measured are very variable according to the zones: from 2 mm to more than 25 mm. The reinforcements are often located in the carbonation zone, and present heterogeneous coating thicknesses (from a few millimeters to several centimeters). Carbonation is also observed on the underside of the samples, which could correspond to carbonation by the internal surface, and not by the surface in contact with the atmosphere.

Chloride levels are also highly variable in different areas. High levels of total chlorides were found on the south facade (0.87% mortar mass on the 15-25 mm fringe), on the east facade only in the gray support mortar (0.31% mortar mass on the 10-20 mm fringe), and on the north facade (0.08 to 0.12% mortar mass on the 0-20 mm fringe). The values are higher than the threshold of 0.06% by mass of mortar, threshold usually retained in the case of reinforced concrete, Corrosion diagnosis observations are shown below in Figures 2 to

3. Those pathologies are described by coauthors on such buildings built close to the seashore [1,2].

Fig. 2. a) Highly corroded surface, b) Materials, cement mortar and bricks with oxides

Fig. 3. a) Highly corroded surface of the steel column east side of the staircase, middle area, b) Corroded surface of the metal girder, near the roof east side

Three major restoration projects appear to have been carried out on the façade decoration in 1934, 1959 and 1995. The current pink color of the plaster, combined with the white decorations, dates from 1971. Previously, the facades were beige with ochre decorations.

Following the progress of the work on the east facade and the north return of the Ephrussi de Rothschild villa, new problems have arisen. Indeed, the openings made in the metal framework of the staircase showed a significant corrosion of the posts, leading to a structural insufficiency, highlighted by a structural engineering office. In addition, water infiltrations in the roof and the terrace, which should have been stopped with the works undertaken in recent years, were still present.

The structural reinforcement proposed by the design office for the staircase, Figure 4, consists of bracing the two pillars with a fiber-reinforced concrete "sock", after stripping and anti-corrosion treatment of the various parts making up the metal posts. The lintels are treated in the same way and covered with new materials based on hydraulic binder.

The structural design manager indicated that calculations take into account the contribution of the primary steelwork. It was therefore essential to reduce its corrosion and not to let it resume. The impossibility of stripping the rear part of the columns, even if it was in a better state of conservation, implied that the areas of concrete polluted by chlorides and affected by carbonation, even in small quantities, would not be eliminated and that the corrosion products also polluted would remain in place. This situation risked generating, in case of water penetration in sufficient quantity (façade, capillary rise, roofing problem), a resumption of corrosion on the back part of the unstripped and chloride-polluted columns, and/or a corrosion by induced anode effect at the stripped-stripped interfaces, and this even if the metal frame is entirely covered by the concrete cladding (especially if the chloride pollution is high, even occasionally).

Fig. 4. a) Initial drawing of the Staircase, b) east and north façade of the villa

A study was therefore carried out on a preventive solution of cathodic protection by galvanic anode, with the aim of stopping corrosion if the conditions favourable to its development are met. This implied a calculation of the system (network of anodes...), a design on its implementation, and on its durability in dry or wet context. The use of galvanic anode is not really documented on historical buildings as it is for impressed current system implemented since the beginning of the nineties, [3,4,5,6,7].

2 Design

The design brief was written on the assumption that during the reconstruction of the pillars, except for the inner face of the profiles on the interior side of the villa (which would remain inaccessible), the metallic profiles would be prepared by sandblasting and then coated with an epoxy coating (2 layers with a topcoat adequate for the adhesion of rebuild concrete). The objective of this application is to limit the current demand to the residual or future coating defects on the accessible parts of the profile and to make it possible to protect the uncoated and inaccessible parts of these profiles, mainly the back side.

In the context of this project, given the anode/cathode surface ratio, the anode length, the very short distance between anodes and cathode, and the very short length of the cables, the calculations of the voltage drop, anode and cathode resistance, and the linear resistance of the cables were not integrated in the design phase as they were considered non-contributory to the operation of the cathodic protection system.

On this basis, the assessment of the expected lifetime of the zinc sacrificial anodes in concrete was carried out by applying Faraday's law to determine the mass of zinc, as a function of the intensity of the protective current supplied by the anode during a given period.

$$tf = \frac{M \times u \times \varepsilon}{8760 \times I_d}$$

T_f : Lifetime of the system in year
I_d : Average current flow (mA)
M : Mass of zinc used (g)
8760 : Number of hours in a year
U : Utilization factor = 80 %
E : Electrochemical capacity of the zinc alloy = 780 Ah/kg

This calculation was carried out by integrating current demand with time. The so-called rebalancing period prior to the stabilised phase varies according to numerous parameters, but experience shows that it is of the order of a few months to a year.

In this way the average value will be adjusted according to the duration ratio between the initial rebalancing period and the measurement period in the stabilized phase.

Table 1. Zinc mass calculation

Protection of the inner bare surface			
Protection current density J_{prot} (mA/m²)	**15**	**12**	**10**
Duration of protection (years) = f(J_{prot})	**0,5**	**1,5**	**38**
Total expected life (years)			**40**
Zinc mass per m² of developed steel	105,3	252,8	5 337,1
Developed steel surface (m²) per pillar	1,32		
Total mass of zinc required (g)	**7 518**		
Protection of the coated surface			
Protection current density J_{prot} (mA/m²)	**15**	**12**	**10**
Duration of protection (years) = f(J_{prot})	**0,5**	**1,5**	**38**
Total expected life (years)			**40**
Mass of zinc per pillar (g)	24	71	1 804
Total mass of zinc required (g)	**1 899**		
Protection of the bare duplex reinforcement cage			
Protection current density J_{prot} (mA/m²)	**15**	**12**	**10**
Duration of protection (years) = f(J_{prot})	**0,5**	**1,5**	**38**
Total expected life (years)			**40**
Zinc mass per m² of developed steel	10,5	31,6	800,6
Developed area of duplex steel (m²) per pillar	7,48		
Total mass of zinc required (g)	**6 303**		
Available zinc mass per pilar (g)			
Mass of zinc per meter of anode (g)	1 770		
Utilization factor (%)	80		
Actual useful zinc mass (g)	1 416	total zinc	
Available zinc mass per pillar (g)	**15 576**	15 720	**OK**

The sacrificial zinc anodes selected are 1 metre long, 1.770 kg/m, pre-embedded in an activated mortar in order to maintain the zinc active throughout the expected life of the implemented anode system.

The measurement points consist of a reference electrode and an activated Titanium/MMO depolarisation probe, which makes the system more robust over time and minimises long-term maintenance work by avoiding the replacement of reference electrodes when they have become polarised, as shown in Figures 5 and 6.

Fig. 5. Anode and RE placed along the steel column

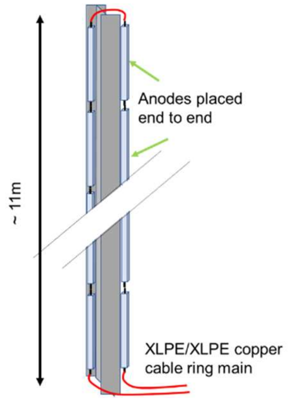

Fig. 6. Schematic diagram of the anode installation

The measurement points were positioned as shown in Figure 7. The reference electrodes and depolarisation probes were pre-sealed in a specific mortar before being mechanically fixed to the duplex reinforcing steel.

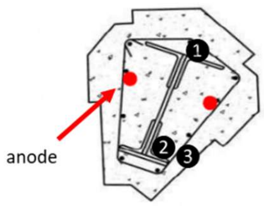

Fig. 7. Anode and RE location (1-2-3)

3 Results

During the commissioning phase, it was observed that the reference electrode ER1 on pillar 1 gave wrong values in comparison with the associated decay probe. This element was rejected and does not appear in Tables 2 and 3.

Table 2. Settings and performance check on steel cathode

RESULT AFTER 3 WEEKS POLARISATION							
Potential (vs Mn/MnO2) & potential difference (mV)							
		Steel of concrete potential					
Zone	Electrode/probe	Native	ON	Instant OFF	**Pol. shift**	24H depol	**Depol. decay**
Pillar 1	Electrode ER1	-	-	-	-	-	-
	Decay probe SD1	-239	-325	-316	**-77**	-206	**110**
	Electrode ER2	-234	-358	-349	**-115**	-276	**73**
	Decay probe SD2	-196	-317	-305	**-109**	-193	**112**
	Electrode ER3	-358	-502	-496	**-138**	-373	**123**
	Decay probe SD3	-199	-318	-306	**-107**	-192	**114**
		Current (mA)		38			
Pillar 2	Electrode ER1	-367	-543	-540	**-173**	-363	**177**
	Decay probe SD1	-159	-337	-323	**-164**	-157	**166**
	Electrode ER2	-363	-580	-560	**-197**	-378	**182**
	Decay probe SD2	-222	-355	-338	**-116**	-165	**173**
	Electrode ER3	-308	-473	-454	**-146**	-292	**162**
	Decay probe SD3	-167	-320	-295	**-128**	-129	**166**
		Current (mA)		29,7			

Table 3. Settings and performance check on Zinc anode

RESULT AFTER 3 WEEKS POLARISATION							
Potential (vs Mn/MnO2) & potential difference (mV)							
		Anode to concrete potential					
Zone	Electrode/probe	Native		Instant OFF	**Pol. shift**	24H depol	**Depol. decay**
Pillar 1	Electrode ER1	-		-	-	-	-
	Decay probe SD1	-914		-648	**266**	-834	**-186**
	Electrode ER2	-1006		-705	**301**	-902	**-197**
	Decay probe SD2	-872		-638	**234**	-821	**-183**
	Electrode ER3	-1037		-830	**207**	-1000	**-170**
	Decay probe SD3	-877		-643	**234**	-820	**-177**
Pillar 2	Electrode ER1	-977		-828	**149**	-955	**-127**
	Decay probe SD1	-757		-619	**138**	-750	**-131**
	Electrode ER2	-989		-858	**131**	-971	**-113**
	Decay probe SD2	-949		-635	**314**	-758	**-123**
	Electrode ER3	-905		-770	**135**	-884	**-114**
	Decay probe SD3	-798		-603	**195**	-722	**-119**

The compilation of tables 2 and 3 allows to calculate the ohmic drop on each of the measuring electrodes. Table 4 gives these values.

From the values of native potential, OFF potential, and ΔE, we can build the polarization diagram presented in figures 11 and 12, and obtained for ER2 and ER3 location for each pillar.

It can be seen that the value of the ohmic drop is approximately the same for the 2 pillars indicating an equivalent electrochemical behavior of the electrolyte (relative humidity, resistivity, temperature, …).

On ER2, there is a difference in the native potential of steel, more positive for pillar n°1, while the native potential of zinc anode is similar for both pillars.

On the contrary for ER3, the native potential of zinc anode in the case of pillar n°2 is more positive than that of pillar n°1 for native potential of steel similar for both pillars.

This shows that the greater the potential difference, the higher the current for the two ER location.

The difference in native potential for pre-embedded zinc anode in an active mortar is often observed and not really documented. Table 3 shows that for the same type of reference electrode, Mn/MnO_2 or Ti/MMO, the native potential.

Table 4. Evaluation of ohmic drop per pillar

RESULT AFTER 3 WEEKS POLARISATION							
Potential (vs Mn/MnO2) & potential difference (mV)							
Zone	Electrode/probe	Native cathodic	OFF cathodic	Native anodic	OFF anodic	ΔE ohmic drop	R Global resistance ohm
Pillar 1	Electrode ER1	-	-	-	-	-	-
	Decay probe SD1	-239	-316	-914	-648	332	9
	Electrode ER2	-234	-349	-1006	-705	356	9
	Decay probe SD2	-196	-305	-872	-638	333	9
	Electrode ER3	-358	-496	-1037	-830	334	9
	Decay probe SD3	-199	-306	-877	-643	337	9
		Current (mA)		38			
Pillar 2	Electrode ER1	-367	-540	-977	-828	288	10
	Decay probe SD1	-159	-323	-757	-619	296	10
	Electrode ER2	-363	-560	-989	-858	298	10
	Decay probe SD2	-222	-338	-949	-635	297	10
	Electrode ER3	-308	-454	-905	-770	316	11
	Decay probe SD3	-167	-295	-798	-603	308	10
		Current (mA)		29,7			

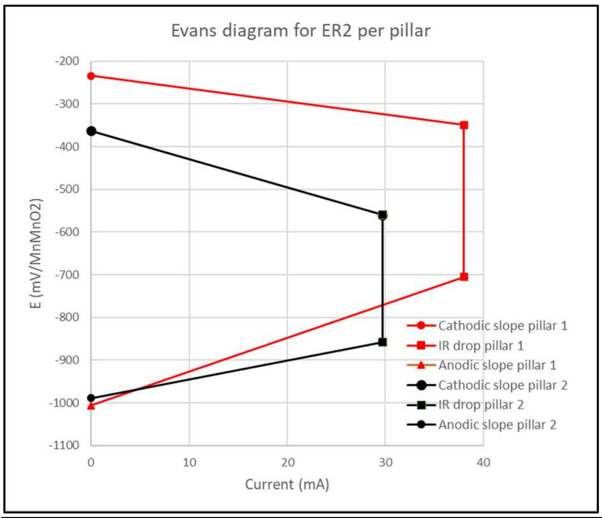

Fig. 8. Polarization diagram obtained on ER2 for both pillars

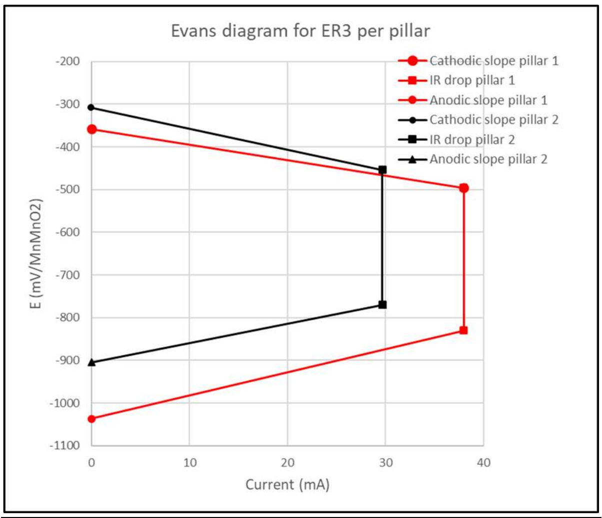

Fig. 9. Polarization diagram obtained on ER3 for both pillars

Nevertheless, according to table 2, pillar n°1 is less polarized than pillar n°2 while the coupling current is more important. We can hypothesize that the surface to be protected is more important for pillar n°1 soliciting zinc anode.

The following criteria are used for assessing the effectiveness of the cathodic protection systems of reinforced concrete structures, [8,9].

An instant-off potential more negative than -720 mV versus Ag/AgCl 0.5M KCl electrode. A 100 mV potential decay from instant-off in 24 hours after current interruption.

For both pillars, the second criteria is met for all reference electrodes except ER2 of pillar n°1.

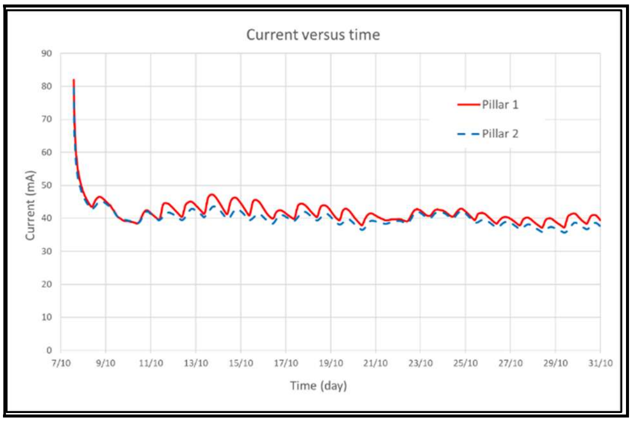

Fig. 10. Current density for the first weeks on the 2 columns

The reduction in the intensity of the protective current (I_{prot}) provided was achieved over the first 5 days following the commissioning of the installation, after which the evolution of I_{prot} as a function of the evolution of the temperature (and therefore of the resistivity of the electrolyte constituted by the reinforcing concrete) over 24-hour cycles is observed. Current is shown to be sensitive to temperature of concrete during day/night cycle. It can be expected to have a decrease of current for lower temperature, [10,11].

4 Conclusion

The anode system deployed on this pilot test, with a view to programming larger-scale maintenance work, is an alternative to the discrete Ti/MMO drilled anodes already implemented on other projects in the past, both in France and abroad.

The latter, in order to comply with ISO 12692 [8] and SP0216 [9] standard, is subject to regular measurement within the framework of a multi-year monitoring contract. It enables the second efficiency criterion to be met and thus offers a relevant alternative to the total deconstruction of the structure, which remains one of the major objectives in the rehabilitation of historical monuments throughout the world.

References

1. E. Marie-Victoire, M. Bouichou, T. Congar, R. Blanchard, "Concrete cultural heritage in France: inventory and state of conservation", In Concrete repair, rehabilitation and retrofitting IV: Proceedings of the 4th international conference on concrete repair, Rehabilitation and Retrofitting (ICCRRR-4), Leipzig, Germany (2015).
2. E. Marie-Victoire, M. Bouichou, "Corrosion at low moisture content in both carbonated and chloride polluted concrete – Villa E-1027", Concrete Solutions 2019, MATEC 289, 10007.
3. C.P. Atkins, P. Lambert, and Z. L. Coull, "Cathodic Protection of Steel Framed Heritage Structures", Proc. of 9th Int. Conf. on Durability of Building Materials and Components, Australia, (2002)

4. P. Lambert, C. P. Atkins, "Cathodic protection of historic steel framed buildings", 2005, WIT Transactions on The Built Environment, Vol 83 (2005).
5. G. Crevello and Paul Noyce, "Preserving a Memorial: The Use of Impressed Current Cathodic Protection on a Historic Steel Frame Rotunda", Corrosion 2014, Paper 4172, San Antonio, TX (2014).
6. X. Hallopeau, A. Meillier, O. Lesieutre, E. Marie-Victoire, and M. Bouichou, "Cathodic protection of an iconic building of the modern movement architecture", Corrosion 2021, Paper 16599, Salt Lake City, UT (2021).
7. X. Hallopeau, O. Lesieutre, C. Annede-Villeau, and E. Marie-Victoire, *"Use of CFRP reinforcement anode for the cathodic protection of an iconic building*", Concrete solutions 2022, MATEC 361, 01007 (2022).
8. EN ISO 12696: 2022, "Cathodic Protection of steel in concrete" (Geneva, Switzerland: ISO).
9. SP0216-2016, "Sacrificial Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures", Houston, TX: NACE.
10. X. Hallopeau, E. Moucadeau, R. Giorgini, O. Lesieutre, A. Meillier, and C. Annede-Villeau, "Zinc layer anode applied on reinforced concrete structures", Concrete solutions 2019, MATEC 289, 03004 (2019).
11. D. Whitmore, and G. Sergi, "Long-term monitoring provides data required to predict performance and perform intelligent design of galvanic corrosion control systems for reinforced concrete structures", Corrosion 2021, Paper 16712, Salt Lake City, UT (2021).