MATEC Web of Conferences **361**, 01007 (2022) https://doi.org/10.1051/matecconf/202236101007
Concrete Solutions 2022

Use of a CFRP reinforcement anode for the cathodic protection of an iconic building

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Abstract. This paper reports the use of a new impressed anode for the reinforcement and the cathodic protection of steel reinforced rebars in concrete beams and columns of a French historical monument. It deals with the application of a dual effect of CFRP reinforcement. The application of a DC current on a carbon fiber-reinforced-polymer used both as a structural reinforcement and as a surface anode, allowed to polarize the steel in concrete. It was then possible to combine the strengthening function with the development of a multifunctional composite allowing protecting of steel rebar from corrosion but also the monitoring of repairing function versus time. The key to success in the development of this surface anode-reinforcement was the possibility of obtaining uniform distribution of current. This innovative technique was applied to the conservation of the reinforced concrete beams and columns of an iconic building of the north of France: the Belfry of Le Touquet's city hall

1 Introduction

1.1 Purpose

The concept of TFC², anode reinforcement was previously presented by the author [1][2]. It concerns the use of electrical properties of composites based on carbon fiber fabric to diffuse an impressed current in order to carry out cathodic protection while taking advantage of the mechanical properties of the carbon material to reinforce a concrete structure.

Fig. 1. City Hall and the Belfry

This innovative solution was to ensure the global reinforcement of a Belfry by the inside in the north of France. The City Hall and the Belfry, listed as a historical monument (Fig. 1), were built between 1929 and 1931. The facing is made of solid bricks and stones from North of France, on a reinforced concrete structure column-beam-slab (Fig. 1a). The roof framework is also made of reinforced concrete (Fig. 2b).

Fig. 2. a) reinforced concrete structure column-beam-slab, b) Roof reinforced concrete framework.

1.2 TFC² concept background

CFRP solution (TFC "**T**issu de **F**ibres de **C**arbone" in French) was used to reinforce bent slabs, beams with respect to bending and shearing, compressed columns and stretched elements. It increases the ductility of the elements, in particular those subject to accidental dynamic stresses (earthquakes). Since the resin does not have the properties to conduct electricity, it was necessary to find a solution to improve its electrical conductivity, to reduce the voltage requirement of the system. The envisaged

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solution was to incorporate in the resin a certain amount of conductive powder in order to render the resin electrically conductive.

The carbon fiber-resin composite must be capable of discharging a cathodic protection current sufficient to maintain the rebars in a passive state. This patented solution took the name of Foreva® TFC² for conductive carbon fiber fabric [3]. It has been demonstrated that the carbon was not affected by the anodic polarization but acts as a catalyzer [1].

The model of current discharge into the concrete is as Figure 3. The electronic current runs through the ribbon connector (anode 0) from the rectifier to the carbon fiber matrix (anode 1), and then to the graphite nodule (anode 2) incorporated to the epoxy resin to be discharged at the concrete/resin interface as an ionic current with catalysis of water in oxygen, evolution of O_2, and / or in the presence of chloride, evolution of Cl_2.

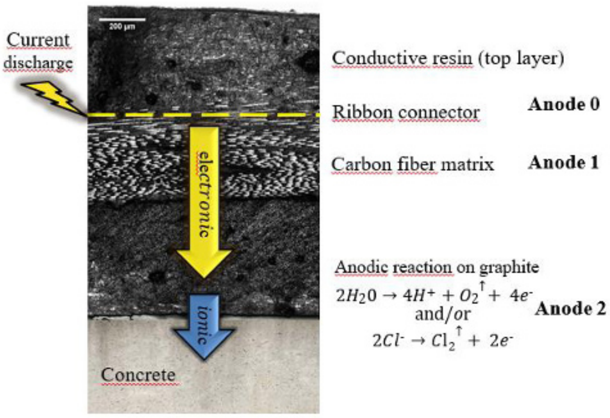

Fig. 3. Current discharge model

1.3 Preliminary diagnosis

In the first step of diagnosis in the Belfry zone performed in 2011 and 2015 [4], visible decay was observed with a predominance of spalling due to intense rebar corrosion (Fig. 4) and superficial granular disaggregation associated with salt crystallization (Fig. 5). The lab analysis of the structural concrete revealed a mix of CEM I, and mainly siliceous rounded aggregates, with a water to cement ratio of 0.85, and an open porosity of 19.6%.

In a second step, the presence of aggressive agents was explored [5]. Thus, phenolphthalein tests evidenced noticeable carbonation depths, with values ranging between 25 to higher than 120mm (Table 2). When compared to the concrete covers (table 1), it means that carbonation was affecting more than the half of the rebars (Table2), even reaching 100% for the external beam of the belfry. These high carbonation depths are to be linked with the high porosity of the concrete and the natural ventilation of the inner belfry.

Chloride concentration profiles were also performed (Table 3) revealing a deep and massive chloride pollution, with values by weight of cement varying between 0.81% and 3.44%. These very high chloride concentrations largely exceed the recommended 0.4% critical chloride threshold for rebar corrosion [6] and are probably due to the proximity of the seashore.

In the last step of diagnosis, potential mapping [7] was carried out in the five upper floors of the Belfry which indicated low to moderate corrosion levels (according to the RILEM Recommendation [8]) associated with visible pitting corrosion. However, the potential measurements were performed in a sunny and warm period, leading to a probable underestimation of the real corrosion activity. The most active corrosion areas were noted on beams abutment and column ends. The initial poor quality of the concrete associated with its high level of degradation gave rise to fears of a deficiency in mechanical performance of the structure especially in areas with high concentration of shear forces and moment reversal.

Fig. 4. Concrete spalling induced by intense rebars corrosion.

Fig. 5. Superficial granular disaggregation associated to salt crystallizations.

Table 1. Concrete cover of the concrete in the Belfry.

Tested area	Minimum concrete cover (mm)	Average concrete cover (mm)
Main column	8	33
Main beam	7	24
Secondary beam	5	35
Chaining	10	18
External main beam	20	67

Table 2. Carbonation depth of the concrete in the Belfry.

Tested area	Carbonation depth (mm)	Proportion of rebars affected by carbonation
Main column	35	56%
Main beam	34	86%
Secondary beam	45	57%
Chaining	25	83%
External main beam	> 120	100%

Table 3. Chloride profiles in the concrete of the Belfry.

Tested area	Depth (mm)	Concentration of chlorides by weight of cement (%)
Belfry zone 1 from the inside	0-20	0.81
	20-40	2.3
	40-60	3.44
Belfry zone 2 From the outside	0-20	3.38
	20-40	1.87
	40-60	1.69

1.4 Conservation project

As the diagnosis indicated that, the concrete was affected by severe corrosion due to a combined in-depth carbonation and massive chloride pollution, with probable mechanical strength issues, it offered narrow possibilities for restoration.

Standard patch repairs [9] couldn't be durable due to the combination of carbonation and chloride pollution. Electrochemical chloride extraction would be only a temporary solution as the chloride pollution was dynamic due to the seashore location, and would anyway not address the carbonation issue durably [10]. So that the only efficient treatment for such a corrosive environment was impressed current cathodic protection. However, the implementation of such a technique remains quite invasive for a historical monument, even if miniaturization attempts were already tested on patrimonial concrete [11]. Nevertheless, in the specific case of Le Touquet Belfry, as the corrosion was very severe and mainly affecting the inner concrete structure, which is not visible from the outside and not open to public visits, ICCP seamed acceptable in relation to the conservation doctrine [12].

Yet, standard ICCP could not address the mechanical strength issue. Therefore, an innovative combination of ICCP and CFRP strengthening was envisaged. The final restoration protocol adopted included the following steps:

- Concrete purging,
- Reinforcement replacing,
- Structure reprofiling,
- CFRP-anode, TFC², application including all impressed current devices to energize and monitor the ICCP system for corrosion control and cathodic protection of steel in concrete,
- Coating application on structure for aesthetical purpose,
- Maintenance contract for ICCP system.

2 Cathodic protection system

2.1 Pilot test

A pilot test was initially conducted to compare TFC² anode efficiency versus Ti/MMO discrete drilled anode and to validate the following objectives:
- Materials and equipment planned for the ICCP work (Anode, reference electrode, depolarization probe, ...),
- Method of installation of the components of the cathodic protection system (preparation of the support, installation of the negative connections, installation of the measuring points, installation of the anode as shown in Figure 6, ...),
- Evaluation of anode influenced zone and spacing to be adopted for job site,
- Protection current necessary to obtain a sufficient polarization to ensure an effective cathodic protection according to the recommendations of the EN ISO 12696 standard [13],
- Validation of anode system capacity to protect the rebars, without creating any over-polarization.

The main conclusion was that TFC² seemed to be more adapted to thin elements. Some previous tests including some carbon meshes into the element seemed to show better efficiency than those obtained with only Ti/MMO discrete drilled anode due to higher anode concrete resistance limiting the applied voltage.

2.2. Design

The final design included the following steps:

- Zoning: 19 zones distributed all along the Belfry on 7 levels with columns, beams and slabs
- Application of a current density in agreement with pilot test results: 15 mA/m² of steel surface
- The diffusion capacity of the TFC² reinforcement anode was on average 10 mA/m² of surface.
- For columns, addition of TFC² anchors to reinforce deeper the columns and also to diffuse current inside the column, as shown in Figure 6 for column and Figure 7 for beam. TFC² anchors closely overlapped the TFC² layer to allow electrical and mechanical continuity.

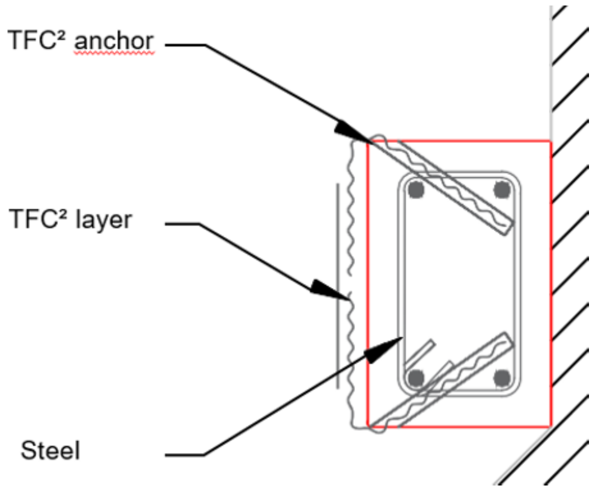

Fig. 6. Anode configuration on column

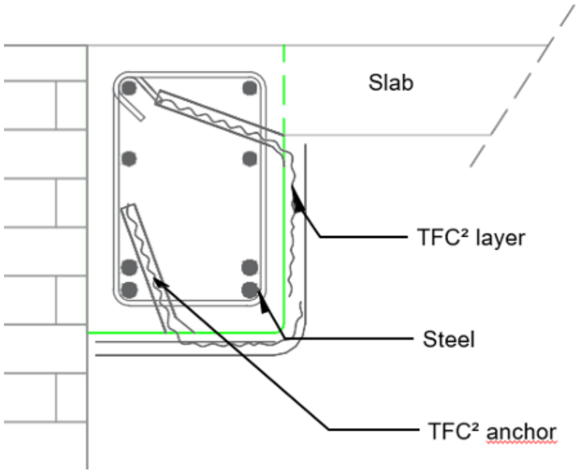

Fig. 7. Anode configuration on beam

The layout of the TFC² was defined according to:

- Structural needs,
- The current requirement for protection of the structure.

The cathodic protection design determined the current requirement of the structure, the zoning as shown in Table 1, and checks that the quantity of TFC², necessary for the reinforcement, was sufficient for this requirement.

DC output voltage of each transformer-rectifier was defined as 24V, for a max DC current output 1A.

2.3 Application of TFC² anode

Prior to application, the concrete surface was prepared by grinding. The electric steel continuity, longitudinal reinforcement, stirrup, top bars, bottom bars, were checked and showed less than 1 ohm resistance according to EN ISO 12696 [4]. In some cases, steel bars were welded to the existing reinforcement to restore electrical continuity.

Table 4. Zoning and current

Zone	Reinforced concrete element	Accessible surface (m²)	Ip [zone] (mA)
LEVEL N1 (13,9->16,5)			
ZONE 1	*Column n°1, 2, 4, 5, 7, 8, 8'*	4,5	54
ZONE 1'	*Column n°3*	0,6	8
ZONE 2	*Beam n° 1 to 8*	20,4	169
LEVEL N2 (16,5->19,4)			
ZONE 3	*Column n°9 to 12*	7,0	151
ZONE 4	*Beam n°9 to 12*	21,9	211
LEVEL N3 (19,4->21,6)			
ZONE 5	*Column n°13 to 20*	3,9	56
ZONE 6	*Beams n°14 to 21*	26,9	305
ZONE 7	*Beams n° 22 to 25*	3,5	43
ZONE 8	*Beams n°26, 28, 30a, 31a*	29,5	495
	Beams n°27, 29, 30b, 31b	13,4	107
ZONE 9	*Beam n°32*	3,9	56
LEVEL N4 (21,6->24,3)			
ZONE 11	*Column n°21 to 28*	4,3	99
	Beams n°34 to 37	3,9	145
	Beams n°38	2,6	26
ZONE 12	*Soffit slab 24,3*	16,2	76
LEVEL N5 (24,3->29,5)			
ZONE 13	*Column n°29 to 36*	18,8	238
ZONE 14	*Beams n°39 to 46*	4,3	99
ZONE 15	*Beams n°47 to 50*	5,6	118
LEVEL N6 (29,5->31,3)			
ZONE 17	*Column n°37 to 44*	5,6	52
ZONE 18	*Poteaux n°45 to 48*	6,0	26
ZONE 19	*Beams n°51 to 62*	5,3	98
ZONE 12	*Soffit slab 31,3*	5,3	25
LEVEL N7 (31,3->33,8)			
ZONE 12	*Soffit slab 33,8*	2,7	13

On each element, a negative connection was welded to the steel. For each monitored element, a measurement connection was added to the negative connection. The anode application is presented in Figure 8.

Fig. 8. Application of CFRP layer on a column

CFRP layer was glued on the concrete surface with an electro-conductive resin, Figure 9.

Fig. 9. Application of TFC² on a beam soffit

Anode wires were connected to the matrix through connectors, as per Figure 10. On each CP zone, a minimum of two ERE-20 electrodes (Mn/MnO_2) and two Titanium/MMO (Metal-Metal-Oxide) potential decay probes were embedded in the concrete to monitor performance of the CP system on different part of locations.

Each electrode was placed in a borehole at a distance of 1 to 4 cm from an existing steel rebar. Each electrode was connected to copper cable type XLPE/XLPE 2.5mm² blue color for reference electrodes and yellow for potential decay probes.

All wires were connected into a junction box located at each level, as shown in Figure 11, and then laid to the main cabinet through a cable tray. The main cabinet, as shown in Figure 12, was located at level N1.

Fig. 10. Anode wiring

All the internal structure was painted with a white acrylic paint for aesthetic reasons but leaving access to the wiring, Figure 10

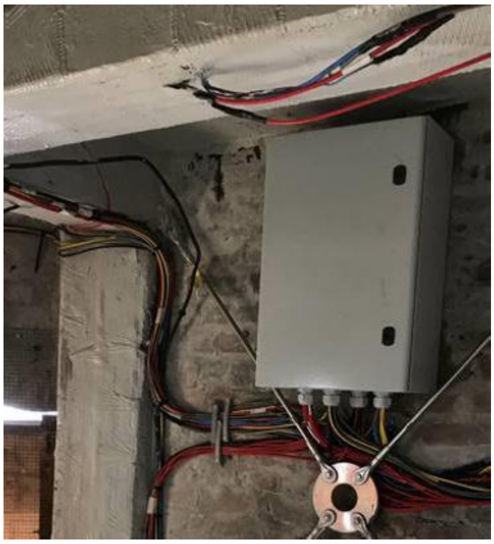

Fig. 11. Wiring and junction box

Fig. 12. Transformer-rectifier Unit and computer

2.4 Data record

The data being measured includes:

- Natural potential
- Polarization time
- Current per zone
- Potential ON
- Potential OFF at 0,1 to 1 second
- IR drop
- Depolarization

3 Results

3.1 Polarization effect on beam

The following criteria were used for assessing the effectiveness of the cathodic protection systems of reinforced concrete structures [13].

- An instant-off potential more negative than-720 mV versus Ag/AgCl 0.5M KCl electrode.

- 100 mV potential decay from instant-off in 24 hours after current interruption.
- A potential decay over an extended period (typically 24 hours or longer) of at least 150 mV from the instant off subject to continuing decay.

Table 5 gives settings and results obtained after 2 months of polarization on the same zones of the pilot test performed 6 months before.

Table 5. Potential shift, current and depolarization decay at 24 hours

Zone	Type	S (m²)	I (mA)	J (mA/m²)	U (V)	Decay probe localization	E_{NATIVE} (mV/MnMnO2)	E_{ON} (mV/MnMnO2)	$E_{INSTANT\ OFF}$ (mV/MnMnO2)	Dépolarization 24H (mV)
1'	Colum n n°3	0,6	6,5	10,8	2,0	Secon d layer	-305	-430	-390	147
						First layer	-288	-502	-449	188
9	Beam n°32	3,9	20,5	5,3	4,5	First layer	-225	-411	-343	153
						Secon d layer	-268	-453	-411	167
						Middle	-287	-517	-460	169

The depolarization results showed a significant effect of cathodic protection on the column and beam reinforcement. For a similar depolarization value, the applied current on column was close to the current design where these obtained for the beam was less.

The efficiency of cathodic protection is controlled inside each element showing that TFC² anchor gives a deeper protection on the inaccessible reinforcement steel layer (back face of column or beam).

4 Conclusion

The preliminary step of diagnosis of Le Touquet city hall Belfry evidenced heavy corrosion of the reinforced concrete inner structure due to both deep carbonation and massive chloride pollution. Mechanical stability was also questioned due to the poor initial quality of the concrete and its high rate of alteration. In a context of historical monument preservation, where both the maximum conservation of the original material and the preservation of the color and texture is targeted, the possibilities of restoration treatment were limited.

The TFC² solution, CFRP and anchor, which offers a double cathodic protection solution, capable of distributing the current both on the surface and in the structure and contributing to the mechanical strengthening of the structure, seemed to be a good option to explore. After a pilot test, the installation on the elements of the Belfry was finalized, the check of the anode-cathode short circuits as well as that of the monitoring devices, and the performance results presented on the same elements as for the pilot test were carried out.

This is a first application in France for an historic monument and from a design point of view a new and complementary solution to the Ti/MMO anode to preserve an emblematic building.

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