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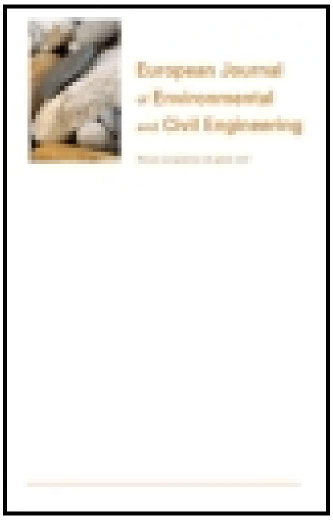

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Conservation techniques on the reinforced concrete pillars of the church of the San Carlo Borromeo hospital in Milan

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Conservation techniques on the reinforced concrete pillars of the church of the San Carlo Borromeo hospital in Milan

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ABSTRACT. *The reinforced concrete pillars of the Church of Santa Maria Annunciata at the San Carlo Borromeo hospital in Milan, designed by the architect Gio Ponti in the early Sixties, show signs of damage due to reinforcement corrosion. They require repair in order to remedy already present damage and also to prevent future propagation. The repair should also aim at preserving the integrity of the original materials, owing to the architectural and cultural value of the Church. The paper describes a trial work aimed at defining an appropriate procedure of restoration. Initially the pillars were inspected to assess their condition by means of non-destructive techniques and analyses on concrete samples. Then the effectiveness of two repair techniques, i.e. electrochemical realkalisation and hydrophobic treatment, was evaluated by comparison with non-treated areas.*

RÉSUMÉ. *Les colonnes en béton armé de l'église Sainte Marie de l'annonciation à l'hôpital San Carlo Borromeo de Milan, conçu par l'architecte Gio Ponti au début des années soixante, montre des signes d'endommagement par corrosion des armatures. Elles ont besoin d'être réparées pour remédier à l'endommagement déjà présent et aussi pour éviter sa propagation. La réparation doit aussi être conçue pour préserver l'intégrité des matériaux, à cause de la valeur architecturale et culturelle de l'église. Cette contribution décrit une tentative pour définir une procédure adéquate pour la restauration. Initialement les colonnes étaient inspectées pour évaluer leur tenue par une approche non destructive sur des éprouvettes de béton. Ensuite, l'efficacité des deux techniques de réparation, la réalcalinisation électrochimique et le traitement hydrophobe sont estimés par comparaison avec les zones non traitées.*

KEYWORDS: *conservation, corrosion, electrochemical realkalisation, hydrophobic treatment, monitoring, reinforced concrete.*

MOTS-CLÉS : *conservation, corrosion, réalcalinisation électrochimique, traitement hydrophobe, monitoring/béton armé.*

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1. Introduction

The Church of Santa Maria Annunciata at the San Carlo Borromeo Hospital in Milan was designed by the architect Gio Ponti and was built in 1964-1967 (Di Francesco *et al.*, 2005). The structure of the Church is made of reinforced concrete and it is finished by brick masonry. The walls are covered with ceramic tiles, while the pillars are in fair-faced concrete both on the internal and external sides (Figure 1). The Church shows clear signs of damage of the materials that constitute the different external elements, such as the coating tiles and the surface of the reinforced concrete pillars.

A project of conservation of the building is being carried out in order to preserve its integrity together with its artistic, architectural and cultural value. In particular, this paper deals with the project aimed at the assessment of the conservation state of the reinforced concrete pillars and at the study of possible conservation techniques.

The degradation of the reinforced pillars is clearly due to the corrosion of the reinforcing bars, as it is shown by the presence of concrete loss and spalling of the concrete cover. Being the Church exposed to a urban environment, the corrosion is likely to be due to the carbonation of concrete, a natural process that causes the alkalinity of concrete, which is initially very high, to reduce and approach neutrality. Steel rebars are protected from corrosion as long as they are in contact with alkaline concrete, while they can corrode after concrete carbonation. So, when concrete carbonation reaches the depth of the rebar, *i.e.* the whole concrete cover is carbonated, corrosion initiates. The rate of corrosion is mainly determined by the availability of water and oxygen in the concrete, and is therefore influenced by the exposure conditions of the concrete element. The corrosion of the embedded steel damages the concrete by causing initially the formation of cracks and then by spalling and swelling the concrete cover. The time necessary for the concrete to be damaged is the sum of the initiation period (*i.e.* the time necessary for the carbonation to reach the rebars), which depends on the carbonation rate and on the thickness of the concrete cover, and of the propagation period (*i.e.* the time necessary for the corrosion products to damage the concrete cover), which depends on the corrosion rate of the steel after carbonation (Tuutti, 1982).

On the external surface of the pillars of the Church some areas are present where concrete has been largely damaged by corrosion (Figure 1); moreover, the presence of some “patch” repairs, which were carried out in the mid Eighties, indicates that concrete damage due to corrosion was already present when the age of the structure was less than 20 years. Many of these previous repairs did not succeed in preventing corrosion to occur again. Therefore, the pillars require an intervention that should remedy already existing damage and avoid future damage occurrence, preserving at the same time the original surfaces and materials of the pillars and reducing their alteration.

a) b)

Figure 1. *a) view of the Southern facade of the Church, and b) damage on a pillar*

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These two requirements are usually in contrast since the traditional repair of a concrete structure damaged by carbonation induced corrosion consists in the removal of all the concrete that is carbonated: in order to guarantee a durable performance of the repair, even carbonated concrete which is still mechanically sound has to be replaced if the moisture content is high enough to promote corrosion of the embedded steel (ACI, 1996; BRE, 2000). This method is clearly in contrast with the need to preserve the original materials and to reduce the alteration of the structure.

There are other repair methods that allow to preserve the concrete that has not been damaged yet, although carbonated (Bertolini *et al.*, 2004). For instance it is possible to apply a hydrophobic treatment on the surface of the concrete, with the aim of keeping it dry enough to stop corrosion, or to apply an electrochemical treatment called realkalisation, that allows to restore the alkalinity of the concrete by means of an externally applied current. Both methods only require the replacement (*e.g.* with a repair mortar) of the concrete that has already been cracked by corrosion. In the case of electrochemical realkalisation, the electrical continuity of the reinforcement should be checked before the application of the treatment.

The work presented in this paper was aimed at studying an approach that started from an accurate analysis of the corrosion conditions of the reinforced concrete pillars in order to assess their conservation state, and then moved to the proposal of repair strategies, with the requirement of reducing the alteration of the structure and promoting the conservation of its aesthetic appearance and its constituent materials, and, at the same time, of guaranteeing an adequate durability. The two methods mentioned above were considered: the application of a hydrophobic treatment and the technique of electrochemical realkalisation.

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The trial work was focused on two pillars: one on the Northern side of the Church (named *4N*) and the other on the Southern side (named *2S*, in Figure 1 it is the second from the right); these two pillars were accessible on their entire height thanks to the presence of scaffolding. The pillars were initially inspected in order to determine their conservation state, by means of on-site non-destructive measurements and analyses of samples taken from the structures. Afterwards, the two repair methods were applied on two small parts of each pillar and their effectiveness was determined by monitoring the corrosion conditions of the rebars after the treatments and by comparing them with the corrosion conditions in non-treated areas.

2. Assessment of the reinforced concrete pillars

The two pillars that were considered were carefully inspected by means of on-site (Subsection 2.1) and laboratory (Subsection 2.2) measurements aimed at determining their conservation state, *i.e.* the cause of their damage, its extent and an estimation of its future evolution (Subsection 2.3).

2.1. *On-site measurements and monitoring*

After an initial visual inspection, the position of rebars was mapped by means of a magnetic profometer and the depth of concrete cover was measured both for longitudinal bars and transverse bars. These measurements were carried out along the whole height of the pillars, at vertical intervals of 0.5 m for the longitudinal bars and at horizontal intervals of 0.2 m for the transverse bars.

Schmidt-hammer test and ultrasonic pulse velocity test were carried out to estimate concrete strength and to check concrete homogeneity.

The corrosion conditions of the rebars were investigated by means of electrochemical measurements, such as the electrochemical potential of the steel. The potential of the steel was measured by means of a high-impedance voltmeter, by connecting the positive terminal to the rebar and the negative terminal to a reference electrode (*CSE*, copper sulphate electrode) that was placed on the surface of the concrete at different positions in order to map the potential of the rebars, at intervals of 0.5 m along the entire height of the columns.

Electrochemical measurements are connected with the corrosion conditions of the steel and the humidity conditions of concrete: therefore, monitoring them in time allows to determine the evolution of these parameters with environmental variations. However, it was clear from the beginning that the presence of scaffolding isolated the pillars from the environment, avoiding for instance their wetting during rain periods. Therefore it was decided to wet artificially the surface of the two pillars in order to allow to characterise the corrosion conditions of the rebars during wet periods. Several artificial wetting cycles were carried out, in the lowest part of the pillars (<10 m), both before and after the application of the conservation treatments.

2.2. *Analyses on materials*

During on-site inspection, samples of concrete were taken from the pillars in order to determine the carbonation depth of the concrete and to make further analyses in the laboratory. The carbonation depth was evaluated by spraying core samples of concrete with a pH indicator (phenolphthalein), which turns to a dark pink colour when the pH is higher than 9 (as in alkaline concrete) and remains colourless when the pH is lower (as in carbonated concrete), thus allowing to detect the carbonation depth. In order to minimise damage to the structure, only 3-4 cores were taken from each pillar, one in the higher part (19-20 m), one in the middle (13-15 m) and one or two in the lower part (4-5 m). In the laboratory, the samples were then subjected to further tests such as the measurement of their density, water content and water absorption and the evaluation of chloride and sodium contents. Small fragments of concrete were also analysed by means of ESEM (environmental scanning electron microscopy), XRD (X ray diffraction) and thermal analyses (TGA/DTA) to investigate the concrete microstructure and the possible presence of dangerous compounds.

2.3. *Results and evaluation of conservation state*

The results of the analyses confirmed that the damage of the reinforced concrete pillars is only due to carbonation induced corrosion. Other causes of deterioration, such as the presence of chloride or sulphate ions or chemical attack, are not present. From the visual inspection carried out on the pillars it can be said that around 10% of the concrete surface is already damaged, while on the rest of the surface concrete has a good cohesion and strength and is homogeneous, except in few localised zones of segregation due to insufficient compaction during concrete placement.

Figure 2 shows the position of longitudinal and transverse rebars detected on the pillars with a magnetic profometer. The diameter is 18 mm for longitudinal bars and 6 mm for transverse bars. Figure 3 shows the minimum and maximum values of concrete cover thickness of rebars as a function of the height of the pillars. Firstly it can be observed that the concrete cover shows a very uneven distribution: for instance on pillar *2S*, moving from top to bottom, the transverse rebars have a cover thickness exceeding 30-40 mm in the highest part of the pillar (>17 m), then the cover decreases to values lower than 10 mm (13-16 m), and it increases again to 30-50 mm, with a great scatter between maximum and minimum values (8-12 m) and finally it reaches values of 10-20 mm in the lower part of the pillar. Also longitudinal bars showed a great scatter in the distribution of the concrete cover.

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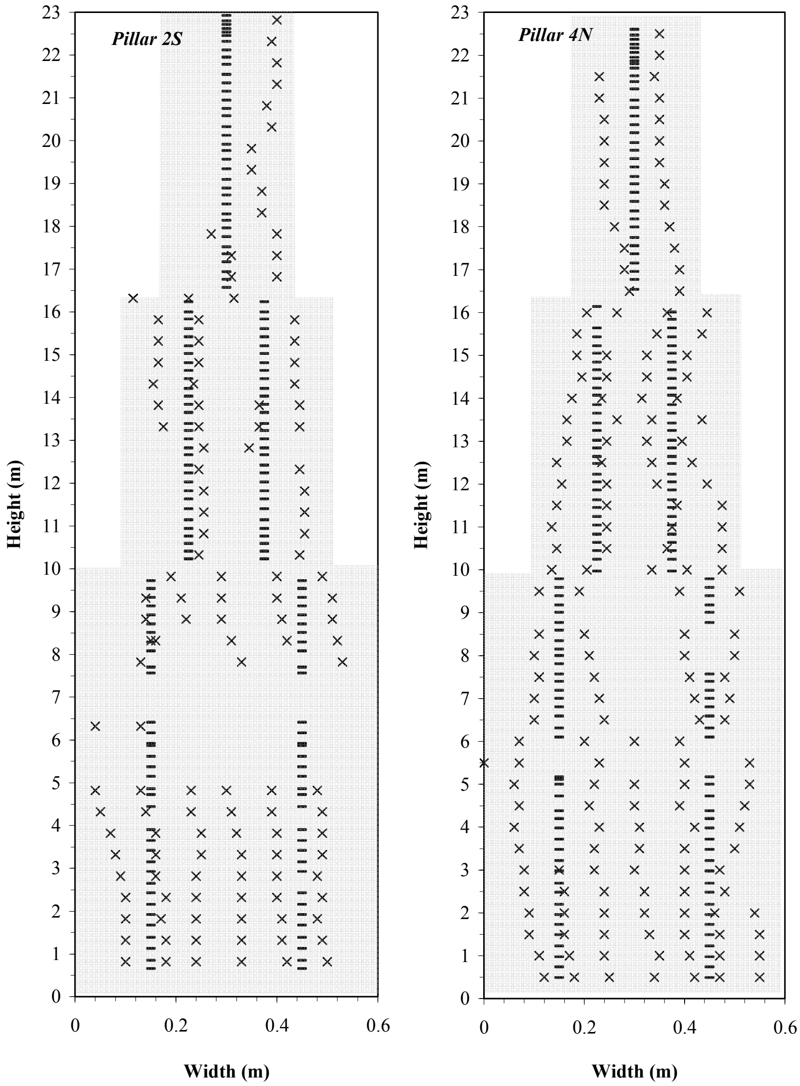

Figure 2. *Position of longitudinal (×) and transverse (–) rebars (detected with a magnetic profometer) as a function of height and width of the pillars (grey area indicates the shape of the pillars)*

Figure 3 also reports the carbonation depths measured on the cores (pink circles). On pillar *2S* the carbonation depth is: nil at an height of 20 m, 7 mm at 15 m and 11 mm at 5 m. In all cases carbonation depth is locally lower than the thickness of the concrete cover: this means that in the points were cores were taken, the rebars are still in alkaline concrete and therefore do not corrode. However, considering the great variability of both carbonation depth and concrete cover, it is not possible to extend this conclusion to other parts of the surface as it is likely that in many zones (in particular in the lower parts of the pillars, where the carbonation depth is higher and the concrete cover lower) the rebars are in contact with carbonated concrete and, therefore, can corrode. This is what has already happened where the concrete is damaged.

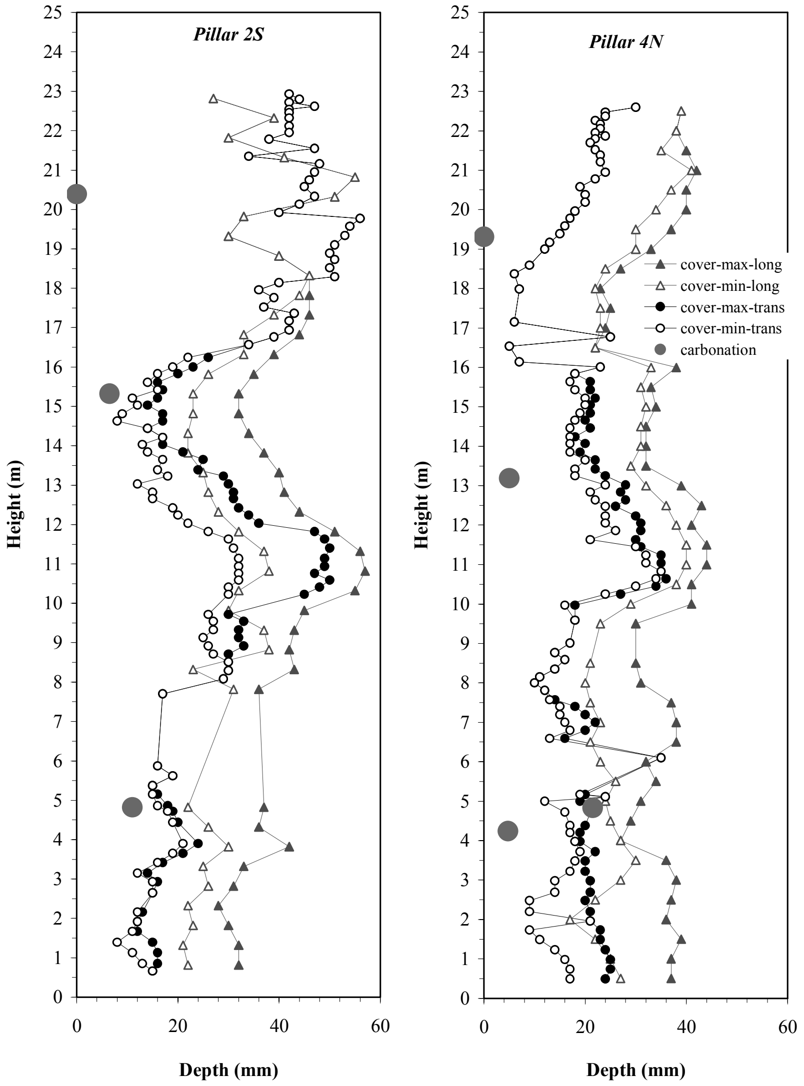

Figure 3. *Maximum and minimum values of concrete cover on longitudinal and transverse rebars and values of carbonation depths at the different heights of the pillars*

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Similar considerations apply for pillar *4N*. Here, one of the cores had a carbonation depth higher than the minimum value of concrete cover; this measurement confirms that there are zones on the pillar where the rebars are in contact with carbonated concrete, but the concrete has not been damaged by corrosion yet.

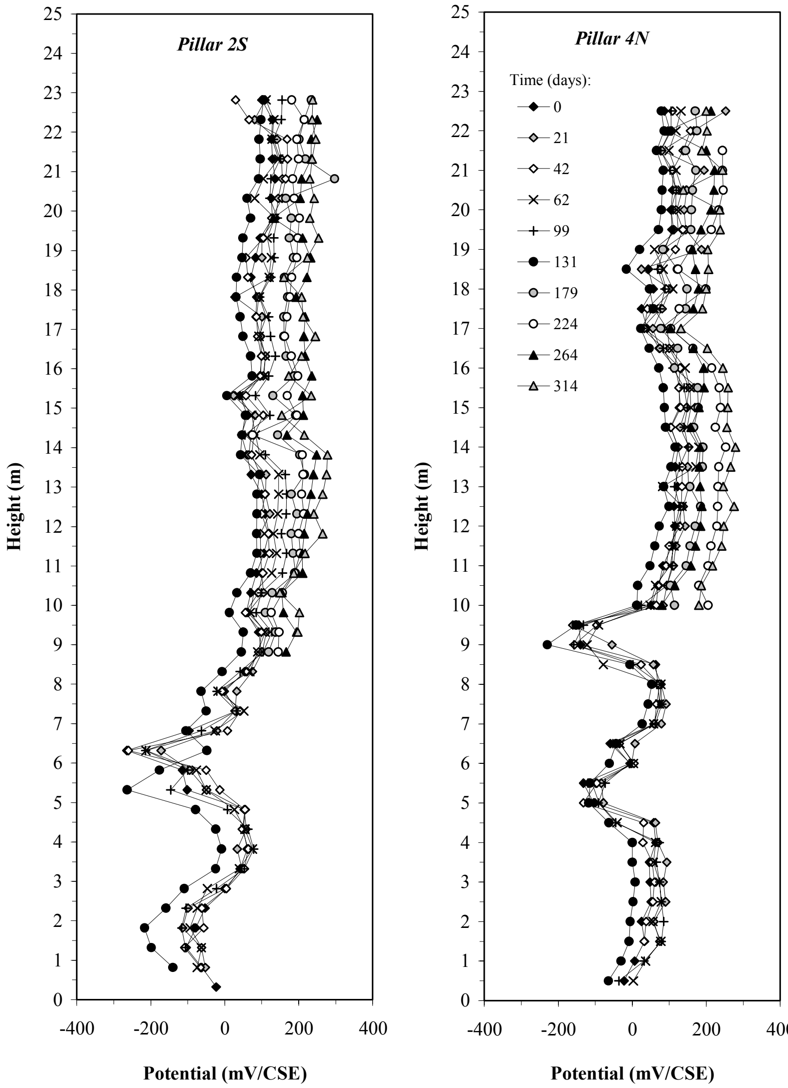

Figure 4. *Natural variations of steel potential in time as a function of the height of the pillars (time 0 corresponds to the month of January)*

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Considering now the corrosion conditions of the rebars, that can be studied from corrosion potential values, the potential mapping on the pillars in their natural conditions (*i.e.* without artificial wetting) showed low values of steel potential (that indicate corrosion) almost exclusively where the concrete was already damaged. This can be seen for instance in Figure 4, that shows the potential values at different heights and at different times for the two pillars. On both pillars, the highest values of steel potential were measured on the highest part of the pillars where, even after natural variations in time, steel potential values were never lower than 0 mV/CSE. This indicates a scarce influence of environmental conditions (in particular humidity) on the corrosion conditions of the rebars, and confirm the sheltering effect of scaffolding. Potential values lower than or close to -200 mV/CSE, that indicate a higher probability of corrosion, were measured on pillar *2S* around 5-6 m and on pillar *4N* around 9 m and 5 m; all these zone are those where the concrete has already been damaged by corrosion.

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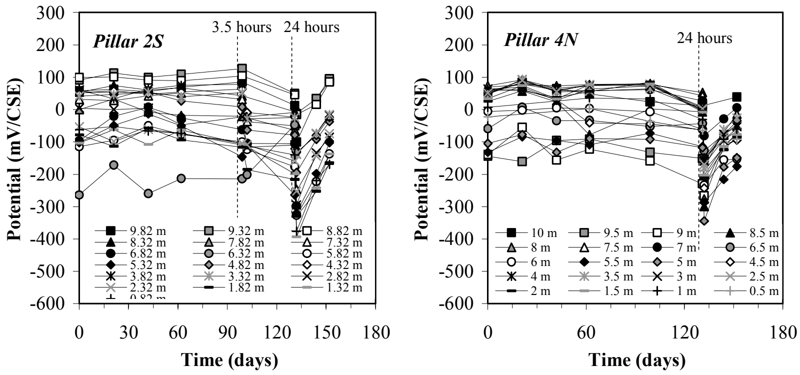

Figure 5. *Steel potential at different heights (in the lower part of the pillars, <10 m) as a function of time. Artificial wettings and their durations are also indicated*

When the concrete surface was artificially wetted to investigate the corrosion conditions of the steel in moist concrete, potential trends shown in Figure 5 were obtained. Since high values of steel potential can be representative both of dry alkaline concrete and dry carbonated concrete, this comparison allows to distinguish between the two cases, as steel in carbonated concrete is expected to undergo a potential decrease after wetting which is much higher than the one for alkaline concrete. For practical reasons, only the lowest part of each pillar (<10 m) was wetted (this lower area was also chosen later for the trial of application of repair treatments). It can be seen that a considerable decrease of steel potential is observed after wetting the concrete surface for 24 hours: on pillar *2S* the average potential decrease is 120 mV and on pillar *4N* 167 mV. The average potential reached after wetting is -200 mV/CSE for both pillars, with values as low as -350÷-400 mV/CSE, that are typical of actively corroding steel. The wetting of 3.5 hours, which was carried out only on pillar *2S*, does not cause significant variations of steel potential (the average decrease was 30 mV). These results show that, although in dry carbonated concrete it is mainly the steel in damaged concrete that suffers corrosion, when the concrete is wet all the rebars in contact with carbonated concrete are actively corroding.

3. Trial of repair techniques

Two repair techniques were applied on selected zones of both pillars. The heights were they were applied are indicated in Figure 6. The non-treated area was used as comparison to evaluate the effectiveness of the treatments. The application of electrochemical realkalisation (Subsection 3.1) and hydrophobic treatment (Subsection 3.2) will be briefly described and then their effectiveness will be discussed (Subsection 3.3). Before the application of the treatments, cracked and damaged concrete cover was repaired with a commercial repair mortar.

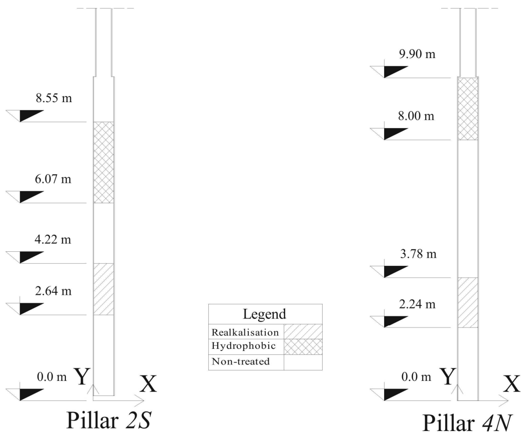

Figure 6. *Zones where the treatments were applied on the two pillars*

3.1. *Electrochemical realkalisation*

Electrochemical realkalisation is a technique that allows to restore concrete alkalinity by means of the application of a temporary external current. The current is applied with a DC generator, connecting its negative pole to the rebars and its positive pole to the anode. The anode is usually a metallic mesh, applied on the surface of the concrete and embedded in an electrolytic system, usually cellulose pulp soaked with a solution of sodium or potassium carbonate. The alkalinity of the

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concrete is obtained by a twofold mechanism (as it is shown in Figure 7): the current produces alkalinity by electrolysis at the rebar surface (so that the rebars are in contact with alkaline concrete and this promotes their repassivation) and the alkaline solution in which the anode is embedded penetrates the concrete from the surface towards its deeper layers. When these two "realkalisation fronts" meet, the concrete cover is completely realkalised. Details on the technique can be found in (Mietz 1995; CEN/TS, 2005; Polder *et al.*, 1992). The technique is mainly applied in Northern Europe; in Italy only few applications have been reported (see for instance (Bertolini *et al.*, 2008)). However there is an increasing interest in this technique, in particular in the field of the restoration of cultural buildings, since it allows to stop the corrosion of the rebars in a non-invasive way, conserving as much as possible the original concrete that, becoming alkaline again, does not need to be removed.

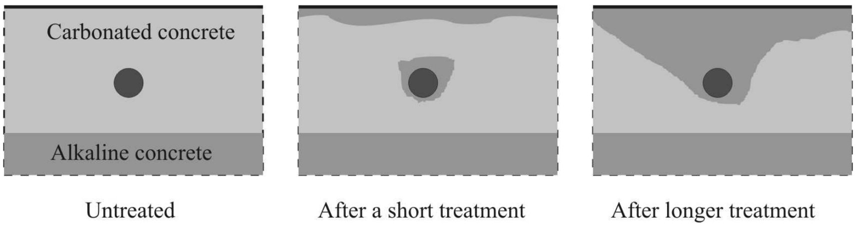
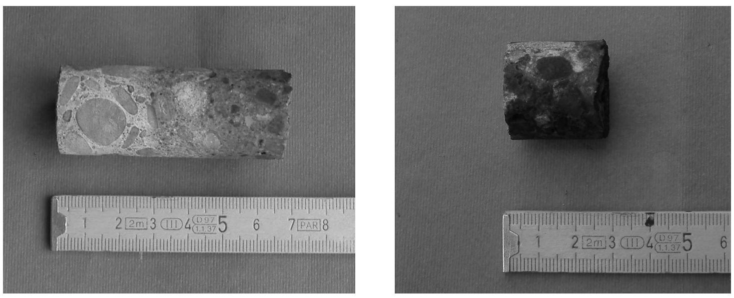


Figure 7. *Evolution of the realkalisation of concrete cover after the application of current (Bertolini* et al.*, 2004)*



a) b)

Figure 8. *Phenolphthalein tests carried out on cores taken from pillar 4N: a) before realkalisation at height of 4.83 m, and b) after realkalisation at height of 3.50 m*

On the pillars of the Church, electrochemical realkalisation was applied with a current density of 1 A/m^2 with respect to the rebar surface for 3 weeks. For the anodic system a mesh of activated titanium and cellulose pulp soaked with a 1 M solution of sodium carbonate (Na_2CO_3) were used. During the treatment, its proper

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functioning was checked by means of potential and current measurements. At the end of the treatment, cores were taken from the concrete to check its alkalinity. Figure 8 shows, as an example, a comparison of the phenolphthalein test carried out before and after the application of the treatment, on two cores taken in nearby areas. It can be seen that initially the carbonation depth was of several tens of millimetres, while after the treatment the concrete was completely alkaline. All the cores that were taken after the treatment turned out to be completely alkaline, indicating that the treatment was completed successfully.

3.2. *Hydrophobic treatment*

Hydrophobic coatings are made of water repellent substances and are applied on the surface of the concrete to reduce the ingress of water and aggressive substances dissolved in it, allowing at the same time its evaporation. They allow to reduce the capillary absorption of water but, keeping the pores dry, they do not affect the ingress of gaseous substances such as carbon dioxide. They can be used in the repair of carbonated concrete structures because they reduce the corrosion rate of rebars maintaining the concrete dry. On the pillars of the Church a commercial product based on silicon resins in water solution was used. Figure 9 shows the surface of pillar *2S* treated with the hydrophobic coating during an artificial wetting.

Figure 9. *Surface of pillar 2S during artificial wetting (the lower part is treated with hydrophobic coating)*

3.3. *Effectiveness of treatments*

The effectiveness of the treatments in protecting the rebars from corrosion was checked by potential mapping carried out both under natural conditions and artificially wetted conditions. The trends of average potential on the three zones (non-treated, hydrophobic and realkalisation) are shown in Figures 10-12. The application of hydrophobic treatment is indicated by a grey dotted line, while the application of electrochemical realkalisation is indicated by a shadowed area; also the artificial wettings and their durations are shown. It can be seen that hydrophobic treatment cannot completely avoid the wetting of the concrete in contact with the steel, as it is shown by the potential decrease after 24 hours of artificial wetting. However the steel potential after 24 hours of wetting progressively increases, and it is always higher than the potential in the non-treated areas, indicating some effect of the surface coating (it should be noted that before the application of hydrophobic treatment the potential in the non-treated areas was more positive than in the areas where the treatment was applied, in particular on pillar *4N*).

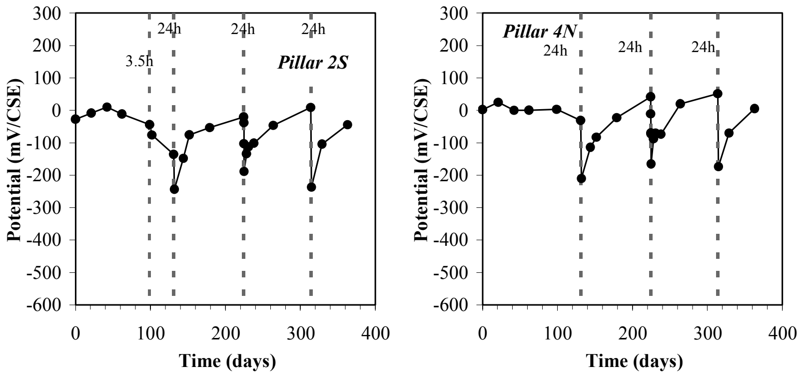

Figure 10. *Average steel potential on the non-treated zones. Blue dotted lines indicate artificial wettings and their duration*

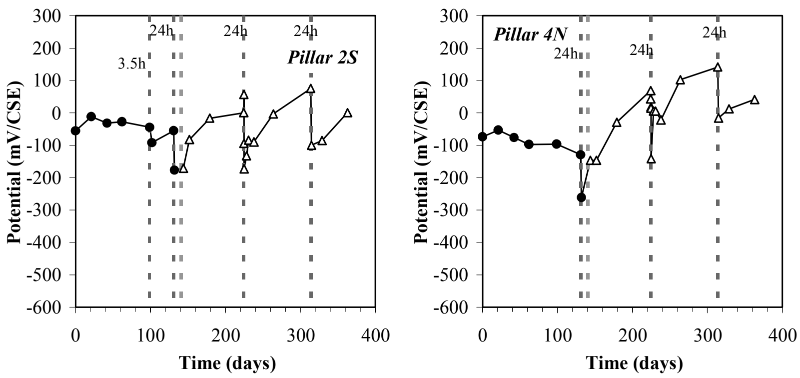

Figure 11. *Average steel potential on the zones with hydrophobic treatment. Grey dotted lines indicate application of hydrophobic treatment*

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Electrochemical realkalisation brought about very negative potential values (due to the cathodic polarisation), around -800/-1200 mV/CSE during the application of the treatment. Potential values in this area remained lower than the initial values and than the values in the other zones, even after 6 months from the end of the treatment. In this case a long term monitoring of steel potential is necessary to assess the corrosion conditions of the steel. However the lower potential decrease after wetting, compared to non-treated areas, is consistent with reduced corrosion rate.

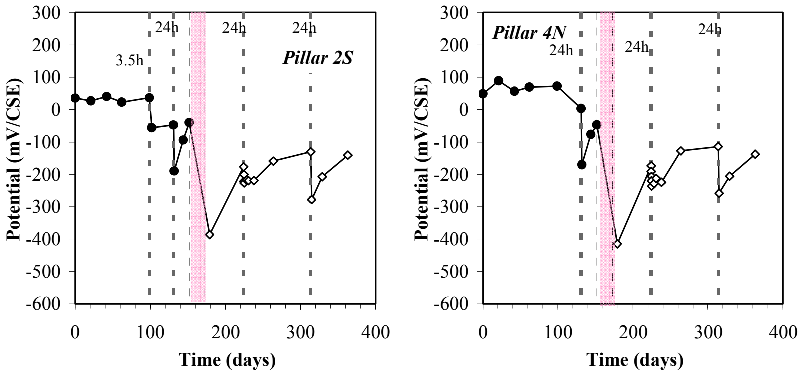

Figure 12. *Average steel potential on the zones subjected to electrochemical realkalisation. Shadowed area indicates duration of treatment*

4. Conclusions

The inspection on the reinforced concrete pillars of the Church of the San Carlo Borromeo Hospital in Milan, which consisted of on-site non-destructive measurements and monitoring and laboratory analyses on concrete specimens, showed that their damage is due to carbonation induced corrosion. A repair intervention is necessary aimed at remedying already existing damage and avoid future damage occurrence, with the strict requirement of preserving as much as possible the original surfaces and materials.

Two conservation methods for carbonated structures were tested on selected areas of the pillars: electrochemical realkalisation and hydrophobic coating. The corrosion conditions of the rebars were monitored in time in order to investigate the effectiveness of the two methods in slowing down steel corrosion.

Electrochemical realkalisation allowed to restore the concrete cover alkalinity: however, it was not possible to monitor the corrosion conditions of the rebars with potential measurements because of the very negative potentials due to the current applied during treatment. The hydrophobic treatment could not completely avoid the wetting of the concrete during artificial wettings. However the steel potential

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progressively increased and its values were always higher than those in the non-treated area, suggesting a decrease of the corrosion rate.

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