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Case study

Corrosion assessment of reinforced concrete elements of Torre Velasca in Milan

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ABSTRACT

An assessment of corrosion conditions, aimed at the detection of the most suitable intervention method, of the reinforced concrete elements of Torre Velasca, which, from the late 1950s, characterises the skyline of the city centre of Milan, was carried out. The facades of the Tower are marked by the presence of structural elements coated with thick and dense layers of render and mortar. In-situ and laboratory analyses showed that the high thickness and compactness of the coating played a positive role in preventing the propagation of carbonation and of corrosion. It was estimated that after 50 years most rebars embedded in concrete were either still passive or free from actively-propagating corrosion. Hence it was concluded that most of the original concrete and coating could be preserved without further protection. However, this repair strategy could be compromised by the risk of loss of adhesion of the coating to the underlying concrete, and this crucial aspect should be better investigated in the design of the repair work.

1. Introduction

Conservation has now become an important issue even for buildings of modern architecture. The preservation of reinforced concrete buildings is a challenge in the management of the cultural heritage, since it requires the development of specific strategies for repair which lead to a reasonable compromise between durability requirements of the repaired building, i.e. a long enough residual service life after the restoration work, and the conservation of the original materials and texture (Marie-Victoire et al., 2008; Bertolini et al., 2011).

The design of the restoration work, and specifically the selection of the most suitable repair technique, requires an accurate assessment of the structure and the materials. As a matter of fact, the actual state of conservation, the extent of damage and the evaluation of its likely evolution in the future, together with the knowledge of the original materials, are crucial aspects.

The study of Torre Velasca building in Milan is emblematic concerning the choice of the suitable repair method for an historic reinforced concrete structure, exposed in urban environment and subject to carbonation-induced corrosion. The tower, from the late 1950s, stands out in the skyline of the city centre of Milan due to its height and unique shape (Kallmann, 1958; Samonà, 1959). Its facades are characterised by the presence of structural elements coated with render and mortar. This paper reports the results of an evaluation of the corrosion conditions of the structural elements, aimed at the definition of the repair strategy, and points out the role of the coating in preventing reinforcement corrosion.

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2. Case study

Torre Velasca was designed by the B.B.P.R. studio and built in 1956–1958 (Fiori and Prizzon, 1982). The tower, which is 106 m high and has 29 floors (Fig. 1), two of which are underground, can be divided in three zones: the lower part, from the ground level to the 15th floor, the intermediate part from the 16th to 18th floor, and the upper part till the 26th floor. The dimensions of the lower and intermediate zones are 21.08 m × 38.46 m; struts and tie-beams, which are present in the intermediate part, support the larger upper part, which is 27.40 m × 44.78 m. The perimeter of the tower is characterised by the presence of projecting load-bearing pillars, beams, struts and T-beams (Fig. 1). According to available documents, major repair works had been carried out on the facades in 1978–1979 and in 1995, due to evident deterioration of structural elements.

3. Experimental procedure

A preliminary visual survey of the facades was carried out, from the ground and from the surrounding buildings, to assess visible signs of damage. A detailed inspection was carried out on elements of the 2nd floor of the N-W facade, which was easily accessible from the roof of a forepart. Further investigations were performed on the same facade at different heights (i.e. 6th, 10th, 14th, 18th and 23th floors) and, moreover, at 6th, 10th and 18th floors of the S-W facade. These investigations required the aid of climbing professionals, since there was no scaffolding.

Non-destructive tests were carried out during the inspection. The cover depth of the outermost reinforcing bars was detected with a magnetic-type covermeter. The corrosion behaviour of the steel reinforcement was investigated by means of electrochemical measurements, mapping the corrosion potential of the steel on the element surface using a copper–copper sulphate (CSE) reference electrode (Elsener et al., 2003). Electrical conductance measurements were carried out by placing a probe connected to a conductivity-meter on the surface of the elements (Polder et al., 2000). The values of electrical conductance were then converted in electrical resistivity values, by means of a constant cell evaluated with a finite elements model. Electrochemical measurements were carried out on the external surfaces, without removing the render.

A sampling, representative of the different types of elements and exposure conditions (i.e. height and orientation), was carried out. Cores were analysed to investigate their stratification, to measure water absorption and the carbonation depth, by means of phenolphthalein test.

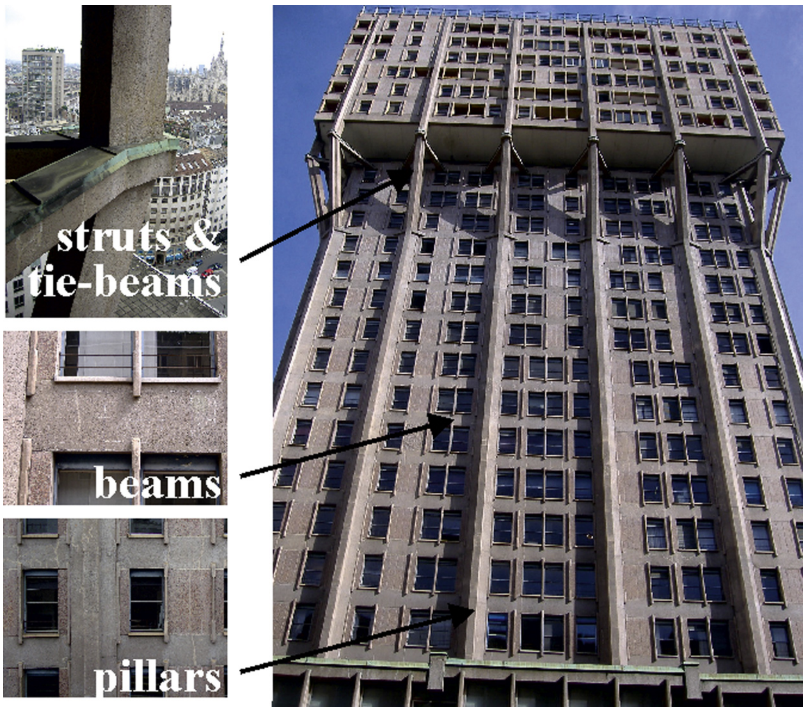

Fig. 1. View of a facade of Torre Velasca and indication of structural elements.

4. Results of inspection

4.1. Visual survey

The visual survey of the facades showed the presence of cracks on the render of the pillars. Most of these cracks had been sealed in the past with a whitish product which made them clearly visible (Fig. 2a). Similar cracks were visible on beams, tie-beams and struts (Fig. 2b). On the struts, the render had been repaired over large surfaces (Fig. 2b). In general, no clear signs of corrosion-induced damage were observed on the elements during the inspection.

4.2. Characterisation of core samples

Sixty five core samples, taken from the different elements, were analysed to assess the nature of the different materials that cover the steel reinforcement and to measure the carbonation depth. Their observation showed the presence of three layers: an external render (*R*), an intermediate mortar (*M*) and the structural concrete (*C*) (Fig. 3). The layer of render was usually adherent to the layer of mortar, which, conversely, was often detached from the underlying concrete. Both the render and the mortar appeared very dense with a low porosity: absorption values of 7.3 and 7.9% were respectively measured, as average value of two samples, on the render and mortar, whilst on concrete an average value of 5.2% was detected. The thickness of each layer showed a great variability: the thickness of render *R* was in the range 5–27 mm, whilst the thickness of mortar *M* was between 5 and 50 mm (Table 1). As a consequence, the total thickness ($R+M$) showed a great variability with values between 12 and 75 mm. The average values were 13 and 17 mm for render and mortar, respectively, and about 30 mm for the total thickness.

Regarding carbonation, in most of the samples the layer of render *R* was fully carbonated, while the carbonation depth of concrete was negligible. The total carbonation depth measured from the external surface ranged between 0 and 56 mm (Table 1). To investigate on possible factors influencing the carbonation depth, results of phenolphthalein tests were plotted versus the position of sampling. Fig. 4 shows, for each type of element, the carbonation depth as a function of the height (expressed as floor number) and orientation. Both the total carbonation depth (filled symbols) and the carbonation depth of the structural concrete (empty symbols) are shown. A systematic effect of either the type of structural element or the local exposure condition did not emerge. For instance, carbonation depths measured on cores taken from the intermediate part of the tower (from 16th to 18th floor), which is sheltered from the rain, were comparable with those measured on the lower and upper parts of the tower. This may be due to the variability of results, which is greater than the effect of local environmental parameters.

In order to investigate on the role of render and mortar layers on the penetration of carbonation, Fig. 5 shows the total carbonation depth as a function of the thickness of $R+M$ layers: the grey area groups specimens with a carbonation depth that is lower than $R+M$ thickness (i.e. concrete was alkaline), while the white area groups specimens where even concrete was carbonated to some extent. It can be clearly observed that in most specimens the carbonation front lays within *R* or *M* layers and, hence, the underlying concrete was barely carbonated. At the time of inspection, i.e. after about 50 years of exposure, even in the specimens with a $R+M$ thickness of only 13 mm, the carbonation depth of concrete was lower than

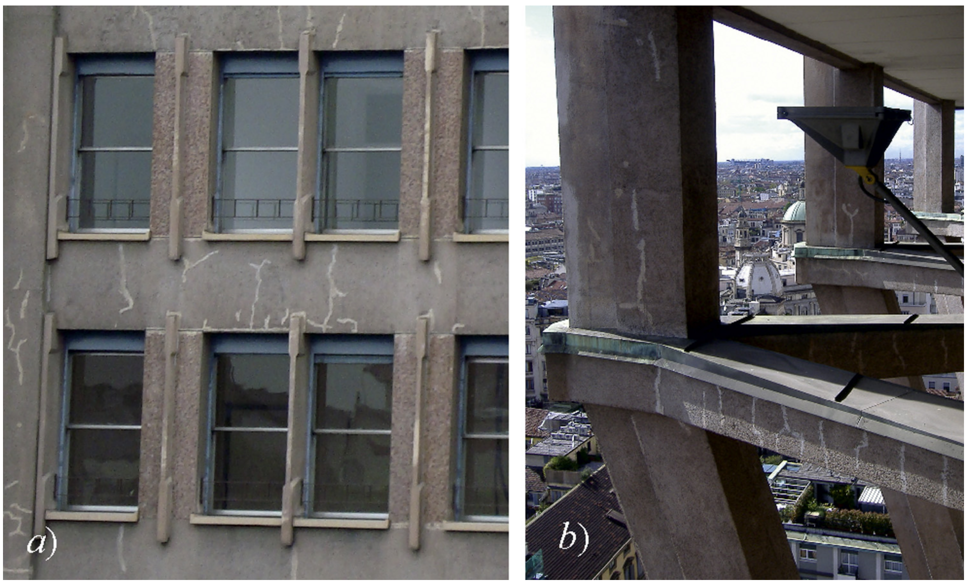

Fig. 2. Details of elements on the facades of Torre Velasca: pillars and beams (a), struts (b).

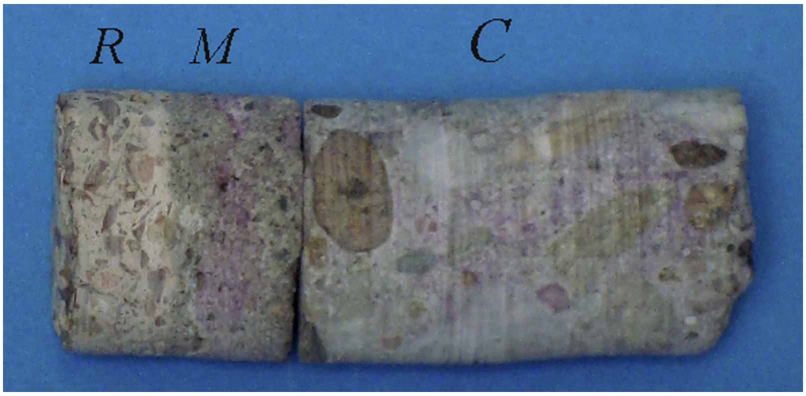

Fig. 3. Typical stratification of a core ($\Phi = 26$ mm) taken from a pillar and designation of layers: R = render, M = mortar, C = structural concrete.

20 mm. When $R+M$ thickness was higher than 30–40 mm, carbonation of concrete was almost completely prevented, indicating that the render and mortar layers had an active role in hindering the penetration of carbonation.

4.3. Cover to rebars

The depth of the rebars was measured from the external surface and, therefore, it included the layers of render and mortar. The cover depth showed a large variability: for instance, on the pillars the depth of the stirrups was between 20 and 75 mm, while for the beams it was between 20 and 80 mm (Table 2). Also on the longitudinal bars a high scatter was observed. This rather high variability is due to both the rebars position and the $R+M$ thickness.

4.4. Rebar corrosion conditions

In order to assess the corrosion conditions of the steel bars at the time of inspection, electrochemical measurements were carried out (Alonso et al., 1988; Glass et al., 1991).

The reinforcement potential measurements, which were incidentally carried out during a rainy period, were performed in the lower part of the building (2nd floor, N-W facade). In addition, potential measurements were also carried out at 6th, 10th and 14th floors on the N-W and S-W facades. It was not possible to carry out electrochemical measurements on elements at floors above 19th, which are more subject to rain. Electrical resistivity was measured on the surface of the elements at 2nd floor in the N-W facade, in the same areas where potential measurements were performed.

Potential values higher than 0 mV/CSE were measured on the rebars at floors below 15th and on some of the struts (Fig. 6a). The electrical resistivity, carried out on the external surfaces, without removing the render, was between 100 and 3000 $\Omega \times$ m, with predominant values higher than 1000 Ω m (Fig. 6b). On the tie-beams the steel potential was measured on the surfaces more exposed to the rain and values between −200 and +150 mV/CSE were measured (Fig. 6a). The rather high values of electrical resistivity and corrosion potential, revealing that the elements below the 18th floor were relatively dry, even during rainy weather, suggested that the layers of render and mortar acted as a “barrier” and contributed to keep the humidity low in the inner concrete.

5. Corrosion assessment

The results of non-destructive tests together with analyses of concrete cores allowed the evaluation of the state of conservation of the structural elements of Torre Velasca and to plan a repair strategy.

Firstly, locations where bars had been already reached by the carbonation front where investigated in order to evaluate the extent of the areas where the reinforcement was no longer passive. Furthermore, for the zones where corrosion was

Table 1
Analysis of the thickness of render R and mortar M and of the total carbonation depth, c, on cores: number of values (#), minimum (m), maximum (M) and average (σ) values in mm.

Elements	#	R			M			$R+M$			c		
		m	M	σ	m	M	σ	m	M	σ	m	M	σ
Pillars	45	5	27	13	5	50	16	12	75	28	0	45	22
Beams	14	5	25	13	6	40	19	12	55	30	0	56	28
Struts	2	13	15	14	6	30	18	19	45	32	13	49	31
Tie-beams	4	7	17	12	18	25	21	27	42	33	0	43	26

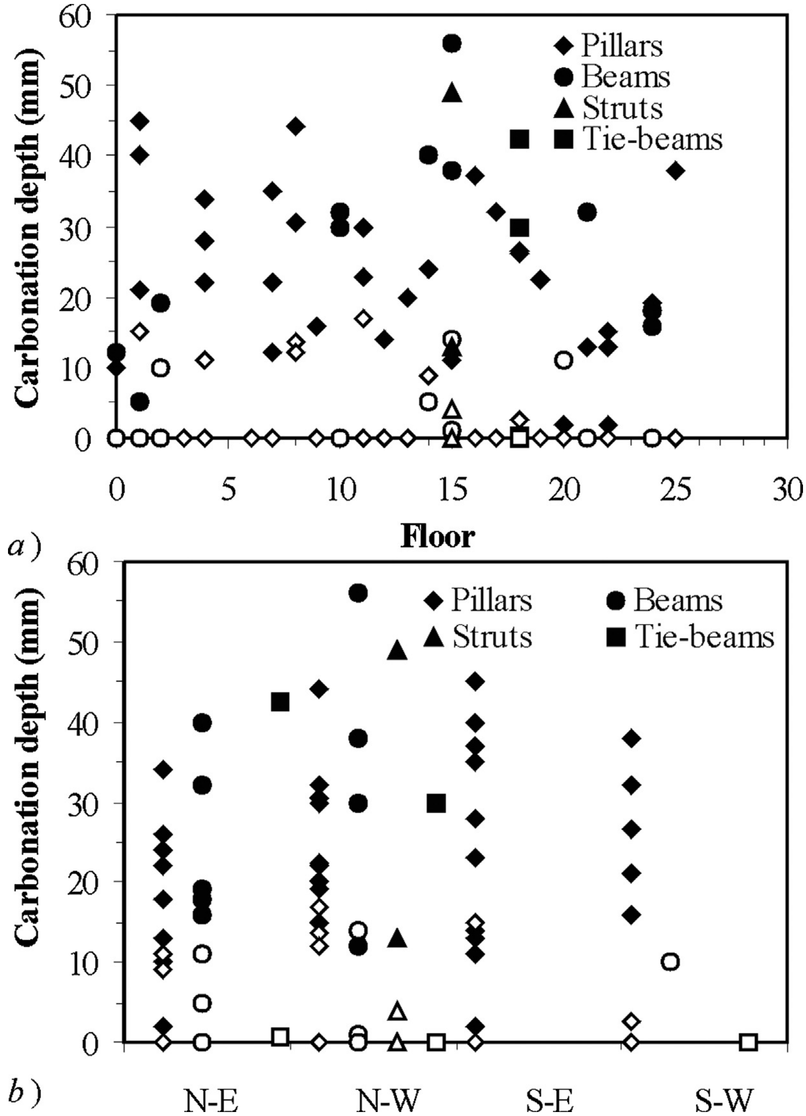

Fig. 4. Carbonation depth as a function of the floor (a) and orientation (b) where specimens were cored (filled symbols: total carbonation depth; empty symbols: concrete carbonation depth).

initiated, the moisture content was investigated to assess if corrosion could propagate. To evaluate the amount of depassivated steel, a statistical approach, which compared the frequency distributions of carbonation depth and concrete cover thickness, was used (Mattila, 2003). Taking into account the data obtained on all the structural elements, it was evaluated that the extent of areas where reinforcement was no longer passive, at the time of inspection, was approximately 20%. This rather low percentage of depassivated steel, after about 50 years of exposure in an urban environment, was likely due to the presence of the thick and dense coating which hindered the penetration of carbonation. Besides the assessment of the extent of depassivated reinforcement, it would have been useful the evaluation of its likely evolution in the future. Unfortunately, the presence of the layers of render and mortar made this estimation rather complicated and the carbonation depth evolution could not be quantitatively assessed. However, it might be supposed that the coating can hindered the ingress of carbonation in the concrete cover, keeping the carbonation depth rather low also in the future and hence, limiting the increase in time of the amount of depassivated steel.

Nevertheless, the role of coating is likely to be even more important for the corrosion propagation in the areas where the steel reinforcement was no longer passive. Indeed, the presence of the coating protected the concrete cover from the ingress of humidity, keeping the concrete dry and delaying the corrosion propagation and its effects, as confirmed by the absence of visible sign of corrosion-induced damage on the element surfaces and the rather high values of electrical resistivity and corrosion potential, although they were carried out in a rather wet period. While it was not possible to carry out electrochemical measurements on the elements of the upper part of the tower, which were more exposed to wetting, it is

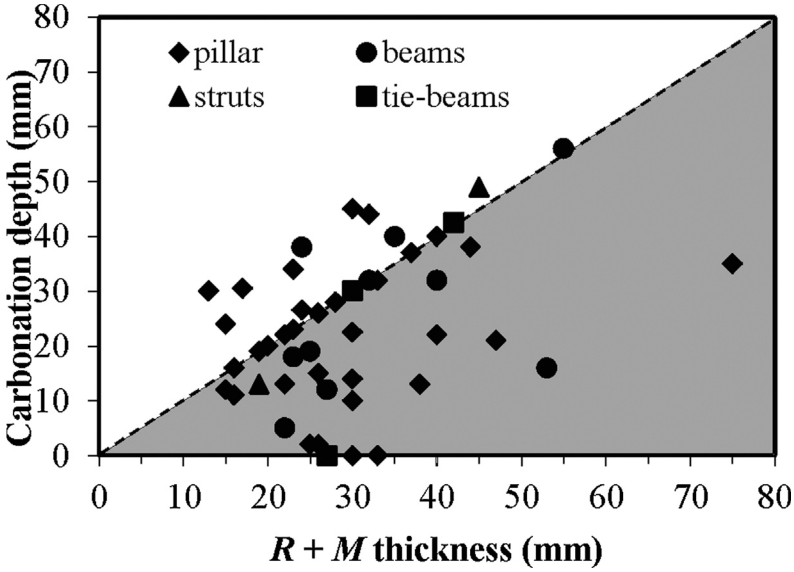

Fig. 5. Relationship between $R+M$ thickness and total carbonation depth.

reasonable to assume that also for these elements the thickness and the compactness of the coating delayed the ingress of water. Hence, it can be considered that the most of depassivated reinforcement is free from actively-propagating corrosion. Even if carbonation would reach in the future the surface of the embedded steel, the concrete in the vicinity of the steel would be only slightly aggressive, due to the low moisture content. Consequently, propagation of corrosion is expected to be negligible.

6. Repair strategy

When the extent of areas where the reinforcement is no longer passive is limited, the conventional repair, which is based on the replacement of non-protective concrete, can be moderately invasive. Otherwise, when a significant amount of sound, although non-protective, concrete is present, other repair strategies should be considered to prevent massive concrete cover removal. For the case of Torre Velasca it was evaluated that approximately 20% of reinforcement was no longer passive at the time of inspection and it was not expected that this percentage significantly increased in the future. However, the damp non-protective concrete was limited, since the render and mortar layers which covered these elements had an active role in keeping the concrete dry. Assuming that this effect will continue in the future, the conventional repair limited to the few local cracked areas, due to the reinforcement corrosion, could be a repair strategy that allows an extensive preservation of the original materials and texture.

However, from the core sampling it was observed that the render and the mortar layers were often detached from the underlying concrete. It is likely that the detachment was also promoted by damage during coring; nevertheless, these results suggest that the mortar-concrete interface is a weak point. Although at the time of inspection there was no evidence of massive debonding of the render and the mortar layers, this aspect needs a careful investigation, not only for safety reasons (consequence of falling of debris would be extremely serious for people in the street), but also because it may affect the performance of the repair intervention itself. In fact, in the absence of good adhesion, the concrete would no longer benefit from the barrier effect against water, and the corrosion of rebars embedded in carbonated concrete could propagate with a rate that will depend on the moisture content. A detailed survey on the adhesion of the render and the mortar layers is necessary during the design of the repair work. In case is it shown that the layers are not well adherent to the underlying concrete over large areas, the previous repair strategy is not applicable. The original materials should then be removed and the application of a new plaster with a cement-based coating, which reproduces the texture of the original plaster, is

Table 2
Analysis of the depth of the rebars: number of values (#), minimum (m), maximum (M) and average (σ) values in mm.

Elements	Stirrups				Longitudinal rebars			
	#	m	M	σ	#	m	M	σ
Pillars	153	20	75	44	154	35	85	56
Beams	77	22	80	42	115	30	85	56
Struts	60	23	68	37	47	22	75	34
Tie-beams	27	19	42	31	19	23	44	33

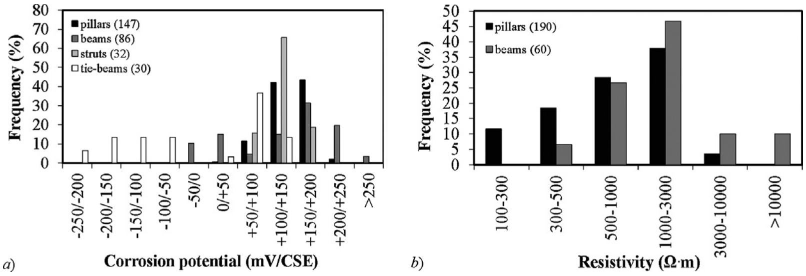

Fig. 6. Frequency distribution of steel potential of the reinforcement (a) and electrical resistivity (b) (number of data in brackets).

suggested (preceded by local patch repair of possible small areas where the concrete cover is cracked). Also the new cement layer is expected to act as a buffer on cyclic moisture changes due to weathering, keeping the moisture away from the concrete. In this way even steel embedded in carbonated concrete would be protected, and the removal of the carbonated concrete will not be needed. If the coating layers are not well adherent to the underlying concrete only in small areas, a re-evaluation of the role of the coating in relation to the penetration of carbonation and the keeping of the moisture away from the concrete as well as on the evolution of the extent of the detachment will be needed.

7. Conclusions

Based on the results of the inspection, the following conclusions can be drawn.

1. A significant effect of local exposure conditions, i.e. height and orientation, on carbonation depth did not emerge.
2. The presence of coating with high thickness, cementitious nature and low porosity both prevented concrete carbonation and delayed the ingress of water into concrete. Hence, most rebars embedded in concrete were either still passive or free from actively-propagating corrosion.
3. A repair strategy based only on the repair of the few local cracked areas is proposed, whilst the sound concrete, even if carbonated, should not be removed.
4. However during the design of the repair works the possible detachment of the coating from the underlying concrete should be assessed and in case the detachment involved large areas the replacement of the original coating with a new cement layer is advisable.

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