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Low durability of concrete elements due to steel corrosion – cases wherein the steel reinforcing bars acted as an internal clock bomb

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Abstract

Concrete elements are expected to resist any process of deterioration to remain its original form, quality and serviceability when exposed to its intended service environment. As the concrete deteriorates durability problems progressively develop leading to structural damage, which might put users in a potential danger. Concrete deterioration may be categorized into three categories of causes: physical, chemical, and mechanical, from which major durability issues come from steel corrosion as a result of combined effect of multi environmental factors. This work reports examples wherein the corrosion of the steel reinforcing bars severely affected the concrete element durability. Five examples wherein the steel reinforcing bars got prematurely corroded, acting as an internal clock bomb for concrete element durability, are reported. It is questioned if the steel reinforcing bars were structurally (un)necessary and if (in)appropriate construction practices were used. Alternative solutions for higher durability are proposed.

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Keywords: Clock bomb, Corrosion, Concrete; Durability, Steel reinforcing bar.

1. Introduction

In today's society, there is a greater awareness of sustainability, whether economically or environmentally. Due to its characteristics, construction industry plays an important role on sustainability, wherein the concrete performance (mainly durability) is the key factor. Being aware that the production of 1 ton of clinker releases approximately 865

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kg of CO^2 owing mostly to chemical reactions and fuel consumption in cement production, it is undoubtedly essential to transform the concrete industry into a green industry, i.e. using concrete more efficiently.

In regards to a more efficient concrete application, nowadays more than ever before, constructors and owners are requiring materials that have to fulfill not only economic demands but also issues like productivity, durability, serviceability, quality and environment. Construction stakeholders are becoming aware that, for instance, in regarding to concrete the cost per m^3 is not the unique criterion to select the most profitable composition and that the acceptance criterion based on the resistance to 28 days is becoming obsolete. Factors like the concrete fresh performance and, especially, the cost per year of the life cycle of the structure are also highly valuable (Aitcin, 2000). In the 21st century, to ensure the sustainability of the construction industry, it is mandatory an increasing use of concrete with high efficiency (i.e. with high durability), as by increasing concrete durability, the amount of concrete is reduced by decreasing the number of applications and natural resources are saved.

Unfortunately, the Madeira Island is an example wherein the economic sustainability is being negatively affected by the low durability of its concrete infrastructures. In fact, numerous of concrete infrastructures constructed in the last 25 years are already presenting high deterioration levels. It is then important to understand why several concrete elements have such high level of deterioration. And, where errors were typically committed?

It is well-known that concrete constituent materials in Madeira Island are quite different than the one used to create standards. For instance, both gravel and sand are from volcanic origin and mostly crushed, consequently to reach a similar workability concrete compositions need higher water and sand contents that cause higher porosity, permeability and shrinkage and lower E-modulus (Maia, 2016). On the other hand, due to its geographical location, as an island, it is surrounded by the Atlantic Ocean which means that most of concrete infrastructure face severe environmental conditions during its service life – most of them are exposed to sea winds or even in several cases in they are direct contact with the sea. Therefore, several questions are arisen: (i) are standards entirely appropriate and/or are they being applied correctly in Madeira Island? (ii) are the usual concrete design/construction practices appropriate? To help to answer these questions this work identifies and reports five examples (all from the Madeira Island) of concrete elements wherein the steel reinforcing bars ('rebars') acted "as a clock bomb" due to its corrosion premature. It is questioned: why steel rebars were employed, if could be they dispensed; how steel corrosion deteriorated and affected the concrete element; what should be done to avoid corrosion and what would be an appropriate construction solution.

2. Steel corrosion in concrete

2.1. Corrosion process

Concrete deterioration may be categorized into three categories of causes: physical, chemical and mechanical, from which major durability issues come from steel corrosion as a result of combined effect of multi environmental factors, occurring when water and ions are able to penetrate into the concrete core. This penetration takes place when interconnections develop between isolated microcracks, visible cracks and pores. Therefore, deterioration is closely associated to cracking as well as to porosity, i.e. concrete durability is mainly related to concrete permeability. Being aware that steel corrosion is the dominant cause of premature degradation of reinforced concrete (Santos, 2014), first it important to understand the corrosion phenomenon.

Corrosion is an electrochemical process that results in a loss of function of the element since it produces a new and less desirable material (rust) from the original metal. It requires the simultaneous presence of moisture and oxygen to oxidize the iron in the steel to produce rust (Figure 1.a),b)). As rust occupies roughly six times the volume of the original material, when the process occurs inside of a concrete (steel reinforcing bars) stresses are generated and concrete cracks (Figure 1.c),d)). Consequently, permeability strongly increases, allowing the ingress in the concrete core of more corrosive species that increases corrosion that increases the concrete cracking, and so on. Thus, once corrosion begins in a steel rebar inside of a concrete the process quickly provokes concrete cracks which can appear just as a single crack (Figure 1.e)) or as spalling (Figure 1.f)) or as a delamination (Figure 1.g)).

In terms of chemical reactions, corrosion happens because at the surface of the steel, the major component (iron 'Fe') undergoes a number of simpler changes: $\{Fe \rightarrow Fe^{n+} + n \text{ electrons}\}$. Thus, the iron atom loses some electrons and become a positively charged ion allowing bonds to other groups of atoms that are negatively charged. The free electrons at the presence of water and oxygen creates the group OH^- by the reaction $\{O^2 + 2H_2O + 4e^- \rightarrow 4OH^-\}$ allowing the formation of $Fe(OH)_2$ through the reaction $\{2Fe + O_2 + 2H_2O \rightarrow Fe(OH)_2\}$. By words one can say: Iron + Water with oxygen dissolved in it → Iron Hydroxide. Finally, as oxygen dissolves quite readily in water and because there is usually an excess of it, reacts with the iron hydroxide to origin the hydrated iron oxide (which is the brown rust) $\{4Fe(OH)_2 + O_2 \rightarrow 2H_2O + 2Fe_2O_3.H_2O\}$ (Nimmo et al., 2003).

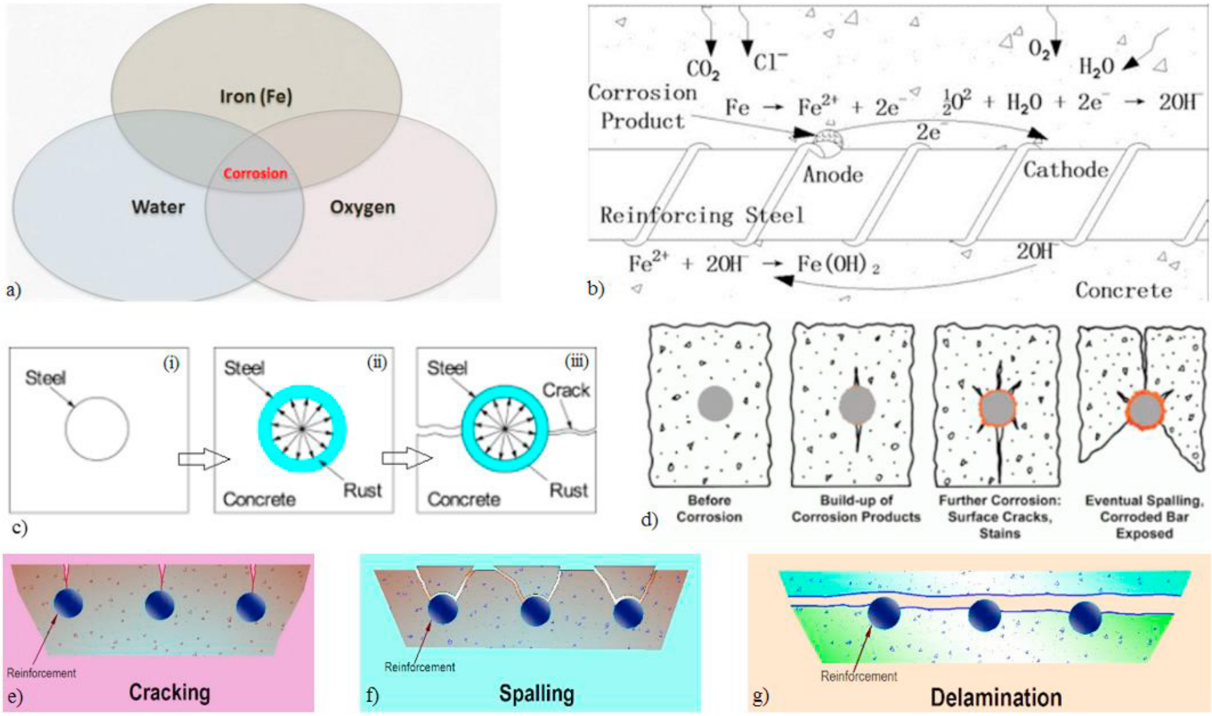

Figure 1. a) Components for corrosion; b) Electro-chemical process of corrosion; c) Generation of stress inside the concrete; d) Evolution of cracks as corrosion progresses; e) Cracks due to corrosion; f) Spalling due to corrosion; g) Delamination due to corrosion.

However, when a steel is in a high alkalinity mean its surface passivates and protects it against oxidation (there is no corrosion). That it happens just inside the concrete wherein the pH is approximately 13 due to the large amount of calcium hydroxide released during the cement hydration. If the pH reduces (for approximately 9.5 or lower) passivation decreases and corrosion starts. The presence of chlorides, carbonation, acid attack or combination of all these, reduce pH of concrete and the steel starts to corrode. It is then important to avoid carbonation and chlorides ingress into the concrete and reach the steel. Thus, as previously referred concrete durability is quite related to its overall permeability (either due to cracks or due to interconnected porosity).

2.2. Consequences in the concrete

From the concrete element point of view, the corrosion of a steel rebar might affect it in two distinct problems: i) steel rebar is affected, its strength is reduced as the corrosion progresses and the rebar loses its functionality; ii) rust production generate stress inside of the concrete which in usually ends in cracks, spalling or delamination, i.e. concrete loses functionality as its covering is destroyed. Usually, when rebars are structurally necessary several cares (specified in codes) are undertaken in order to prevent and delay their corrosion. However, in many cases steel rebars are incorporated in the concrete but they are not structurally necessary. Rebars are placed because they are only temporary necessary (for instance: they are required in fabrication process or applied to avoid early age shrinkage) and consequently corrosion of rebars frequently is not appropriately prevented.

This work is mainly focused in the second problem, being studied and presented examples of concrete elements that could be made without steel rebars; but rebars were used and the concrete element got deteriorated and lost functionality because the production of rust acted as a clock bomb inside the concrete.

3. Examples wherein the reinforcement acted as an internal clock bomb

3.1. Fence / sitting concrete wall

The first example is a typical (in the Madeira Island) concrete wall that function also as a fence and as a sitting between the promenade and the beach (Figure 2.a)). It can be made in a single element poured in situ (Figure 2.e)) or made by two elements with the wall poured in situ and with a prefabricated element in the top (Figure 2.b)). In this type of concrete elements, possibly, the reinforcement would be structurally unnecessary – it looks to be a gravity wall. Perhaps rebars were placed to control shrinkage or due to transport (in the prefabricated elements), but no anticorrosive cares were ensured. Probably this infrastructure would be in a better condition if there was no steel rebars. The reality is: steel rebars got corroded and destroyed the concrete element – they acted as an internal clock bomb! No reinforcement or GFRP rebars should be the correct solution. If steel rebars are used, even if they are just temporarily for the construction (not structurally), corrosion should be prevented.

Figure 2. Fence / sitting concrete wall: a) Element overview; b) Construction with two distinct elements; c) Spalling of edges; d) Advanced cracking of the prefabricated element (cover); e) Full corrosion and delamination of the cover (not prefabricated); f), g) Scheme of the reinforcement corrosion and consequent cracking and delamination; h) Detail of the deterioration of the cover in the no prefabricated element.

3.2. Block concrete wall with mortar and steel rebars at the top

Block concrete walls are being worldwide used. However, it become a typical construction practice in Madeira Island to place at the top of the wall about 5 to 10 cm of mortar with two steel rebar (having 10 mm of diameter) – see Figure 3. These two steel rebars are just placed inside the mortar without no especially care. It is a bad construction practice (that is even not able to prevent the transversal cracking – Figure 3.f)) that leads to the steel rebars to act as a clock bomb into the mortar (Figure 3. b),c),d),e)). Note: mortar is a material with high permeability. No reinforcement would be the best solution with the transversal cracking being perfectly accepted (Figure 3.g)).

Figure 3. Concrete block wall with mortar at the top: a) Element overview; b) Detail of the spalling of edges; c) Advanced cracking and spalling of edges; d) Cracking part; e) Cracking over corroded rebar; f) Detail of the transversal cracking not avoided g) Alternative concrete block wall having transversal cracking but no corrosion and longitudinal cracking.

3.3. Concrete fence

Design concrete fences composed by columns and a beam at the top (as presented in the Figure 4) are quite usual around houses to increase aesthetics. As loads are quite low (wind), usually, no structural cares are taken to its production and steel rebars are placed just to avoid cracking and to link all columns to the beam without prevent its corrosion. However, when the concrete (in many cases, it was used mortar) is of high permeability and cover is not respected, rapidly corrosion takes place. Consequently, cracking spreads like a clock bomb and the aesthetic function of the element is severely reduced (Figure 4.a),b),c),d)). In Figure 4.f),g) are presented schemes about the rebars position and how the corrosion broke the connection between the column and the beam (seen in Figure 4.b),e)). Figure 4.h) schemes what happens when corrosion occurs inside the column (Figure 4.d)). Being aware that quite low loads acts on the element if no rebars were applied, probably the aesthetics of these elements would be much better. Alternatively, GFRP rebars could be applied to ensure good connection between the columns and beam and to control plastic and dry shrinkage.

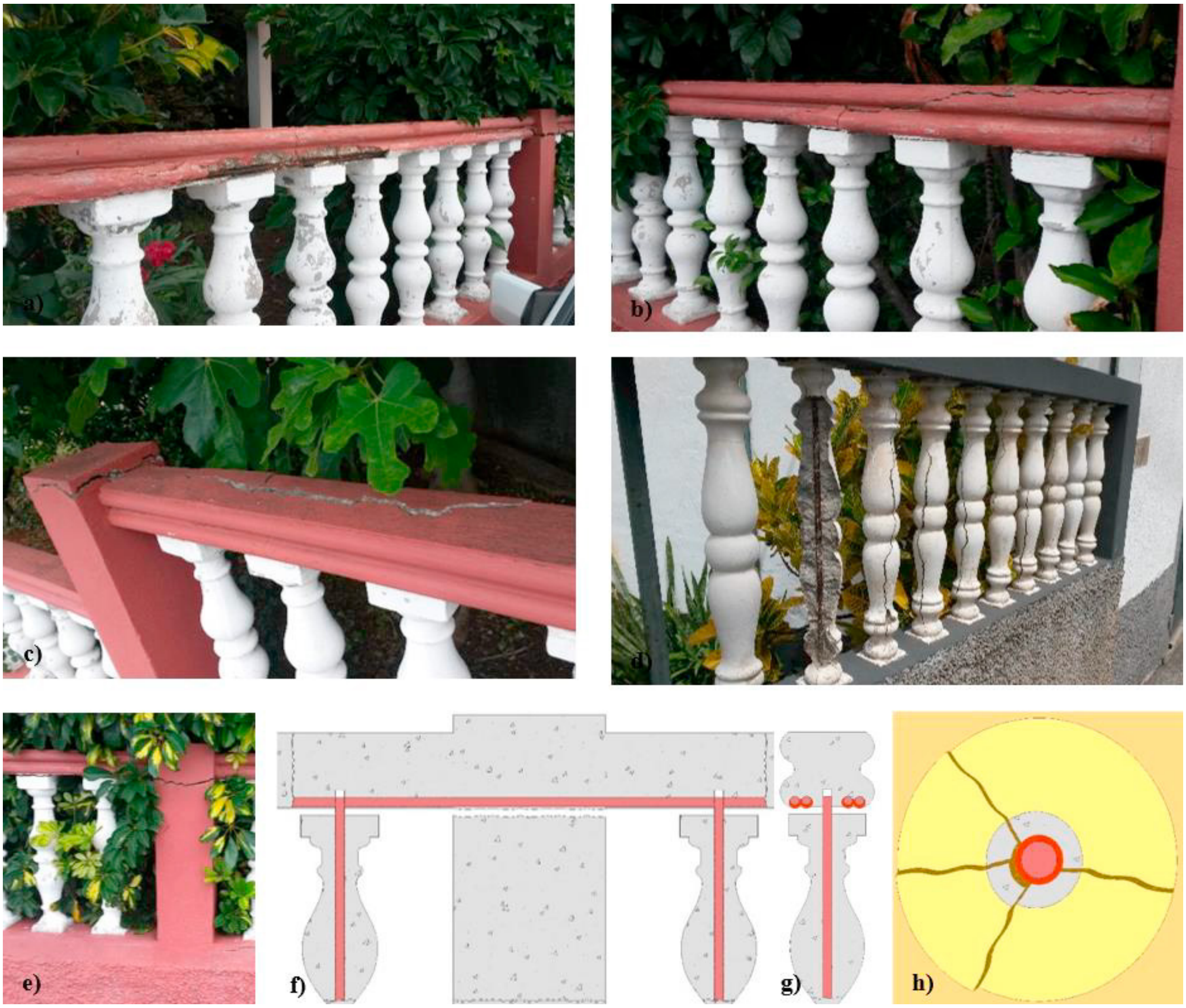

Figure 4. Concrete fence: a) Element overview with advanced corrosion at the bottom of the beam; b) Cracking of the beam with separation between columns and beam; c) Detail of the cracking extension; d) Advanced corrosion in the columns; e) Detail of cracking due to corrosion of the reinforced beam; f), g) Schemes of the elements and the effect of corrosion on the beam; h) Scheme of the column corrosion effect.

3.4. Concrete buttress arch

At the end of the runway of the Cristiano Ronaldo Airport (in the Madeira Island) there a highway which is supported by a concrete buttress arches (Figure 5.a)), being the sea just a few meters behind. Looking close at the construction it can be observed corrosion overall the structure. In some elements, especially in a buttress delamination is generalized (Figure 5.b),c),d),e),f),g)), some rebars having already disappeared or separated from the concrete core (Figure 5.d),e)). The arches show overall cracking (Figure 5.h)), although some parts have been already repaired (Figure 5.i)). Looking at the structure it is not possible to affirm that rebars were unnecessary (if they were placed just for shrinkage or if they were structurally required). But, the point is: not only rebars are already not there (that means that at the moment rebars are not function as structural), but also the concrete section was markedly reduced (more than 10 cm of cover has disappeared due to delamination). Observing the concrete one perceives that concrete has high permeability and incorporates aggregates with about 5 cm. There was no construction care to prevent the steel rebars corrosion - it was like to put a clock bomb inside the concrete. Being a such important structure, the solution could be: i) to use a concrete with very low permeability (including very low cracking), ii) to apply stainless steel rebars, iii) to apply GFRP rebars, iv) (if possible) to apply plain concrete.

Figure 5. Concrete buttress arch: a) Construction overview; b) Generalized spalling; c) Buttress; d) Advanced spalling with disappearing of the rebars; e) Disassemble of the steel rebars; f), g) Gaps between the cover and buttress core; h) Overall cracking; i) Repairing points.

3.5. Fence / concrete bench

Lastly, it is presented a concrete bench that function as a sitting between the promenade and the beach (Figure 6.a)). Looking at Figure 6 it seems that reinforcement was structurally unnecessary because the structure looks quite rigid due to its geometric shape. Probably, rebars were placed to control shrinkage or to respect codes. But, seeing Figure 6.b),c),d),e) it is clear that concrete is too bad and it has aggregates too large to ensure low permeability to protected the steel rebars – as rebars were not structural, no protection to corrosion was ensured. Thus, steel rebars acted as an internal clock bomb as they got corroded! No reinforcement or GFRP rebars should be a more appropriate solution.

Figure 6. Fence / concrete bench: a) Element overview with delamination in the edges; b) Detail of cracking and spalling; c) Detail of a support with spalling on the edges; d) Detail of the concrete and the steel rebars disappeared; e) Detail of the aggregates dimension of the concrete.

4. Conclusions

Steel corrosion plays a major rule on the durability of concrete elements. To place steel rebars in concrete elements without ensure its appropriate protection against corrosion, it acts as a clock bomb. This problem is especially frequent when steel rebars are placed in concrete elements wherein reinforcement would be structurally unnecessary.

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