Extended Abstract

Conservation and safety assessment of a bridge in marine environment

The case of Faro’s bridge

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1 Introduction

The durability of reinforced concrete structures, exposed to marine environment, is a subject of growing concern these days, because the number of this type of structures with early deterioration has increased. The marine environment is composed with many aggressive elements that have the capacity to start the deterioration mechanisms of concrete and, mainly, of reinforcement. The structure loses its initials characteristics, making it unable to satisfy the functions for witch are designed. Because of that, it is necessary to repair the structure, avoiding maintenance and repair costs that are not planned. In marine conditions, the main deterioration mechanism is due to the action of chloride ions, which causes the corrosion of the reinforcement.

In order to ensure a good performance of the structure in these environmental conditions and avoid expensive repair costs, it is extremely important the existence of monitoring plans, allowing control of structure behaviour over time. The conservation and safety assessment is also imperative, especially in structures where the concept of durability was not taken into consideration, during its construction. It can be done through appropriate diagnostic techniques to each deterioration mechanism.

The Faro's bridge is an old structure which appears to have a high level of deterioration. It is also a structure that wasn't designed for seismic actions. For these reasons, it is important to check the safety of the bridge to vertical actions, which is currently subject, and the possible occurrence of a seism.

2 The relation between concrete and marine environment

The marine environment has, in its composition, ions that cause damages in concrete and reinforcement. The most abundant (55%) [1] is the chloride ion and it is the main reason for the reinforcement corrosion mechanism. When appropriate protection measures are not taken, this ion causes irreversible damages to this type of structures that can put in risk its resistance and consequent safety.

Also the atmospheric environment influences the process of degradation of reinforced concrete structures. The occurrence of high temperatures and intermediate levels of relative humidity also influence this process of degradation. In fact, a high temperature increases the corrosion rate, accelerating the beginning and the development of this mechanism. The moisture is essential to initiate the corrosion mechanism. The heating-cooling and the wetting--drying that the structure is exposed and, also, the performance of other physical actions, like the impact of the waves on the structure and the forces resulting from biological action, causes the cracking of the concrete [2]. Consequently, the entry of aggressive agents into the concrete is facilitated, putting in risk the integrity of the materials.

The quality of concrete has a great influence in the initiation and development of the main processes of deterioration. Indeed, the entry of aggressive agents into the concrete depends on the porosity of this material. If the material has a low percentage of voids, the penetration of these aggressive elements is minimized. Good placement, compactation and curing of the concrete during the construction, a low ratio water/cement and the use of addition, ensure an adequate level of porosity of this material [3]. Over time, also occur reactions in the cement responsible of decreasing porosity levels, as are the cement hydration, the formation of aragonite layer and the reaction of hydrated products of the cement paste with the constituent ions of sea water [3]. It's concludes that the concrete has a high importance in the performance of the structure and its durability, because this material is the first barrier against the penetration of aggressive agents. The quality of the concrete should be adequate to the environmental conditions. This characteristic can be controlled also by the chemical composition of this material, because the deterioration mechanisms are directly or indirectly related to the components of the concrete and the cement paste.

The loss of characteristic of the concrete affects the resistance of the material. The cracking and the delamination of the concrete can also reduce the transversal sections of the elements, the exposure of the reinforcement and its reducing transversal section due the corrosion process, cause the loss of stiffness of the elements and their capacity to resist the imposed actions [1].

3 Deterioration mechanisms of reinforced concrete structures

The degradation of reinforced concrete structures may occur in concrete and/or in reinforcement. In the marine environment, the degradation of the reinforcement has a higher probability of occurrence by the corrosion process. The deterioration of the concrete takes place through its physical and chemical changes.

3.1 Reinforcement deterioration

The concrete acts as a protector of reinforcement. Its high alkalinity (pH=12.5 to 13.5) ensures the existence of a passive film that protects the reinforcement to the corrosion mechanism. The covering layer acts as a barrier to the penetration of aggressive elements to the level of reinforcement [4]. The loss of this protection (dissolution of the steel) occurs when: (i) occur the lowering of the pH due to carbonation process (pH <10 [5]), or (ii) penetration and reach the critical chloride content up to the level of reinforcement.

The corrosion mechanism, as all of its elements, is illustrated in Figure 1.

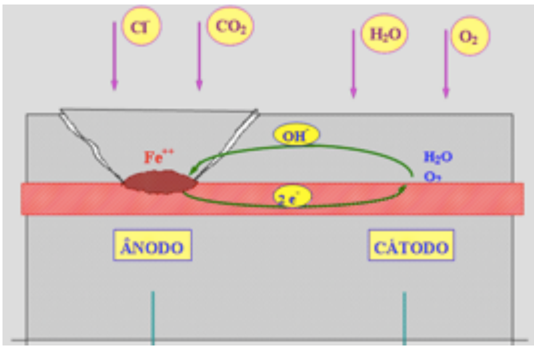

Figure 1 – Corrosion mechanism of reinforcement and all the elements that are involved [6]

The marine environment has many elements responsible for the beginning of the mechanisms of deterioration in reinforced concrete structures. The most abundant element and primarily responsible for the deterioration of the reinforcement is the chloride ion, as has been said. When the critical concentration of chlorides into the reinforcement is attained, in other words, one from which the despassivation of reinforcement occurs, the corrosion process starts.

The carbon dioxide penetration is also responsible for the deterioration of reinforcement. The reaction with the hydroxides present in the concrete causes the loss of its alkalinity and therefore, the depassivation of reinforcement. It is a slow process, occurring over several years [7].

The combination of these two processes can cause very high corrosion rates.

Oxygen is also an essential element to the beginning of the corrosion process, as well as the presence of moisture.

3.2 Concrete deterioration

In addition to the physical actions that may cause the disintegration of the concrete, the deterioration of the material appears even when it is chemically modified.

The penetration of sulphates into it and its consequent reaction with elements of cement paste, especially with tricalcium aluminate (C_3A), originates reaction products whose volume is 2.5 times higher than the products from which they originated [8]. This mechanism causes expansion and cracking of the concrete and loss of its resistant characteristics.

The reaction of alkali (Na_2O and K_2O) with reactive concrete aggregates, that is an expansive reaction, causes irregular cracking and the early degradation of the concrete [5].

Also the acids and ions present in the marine environment may lead to loss of concrete binding characteristics [6]. These are able to decompose the cement paste, to lead leaching and efflorescence and to lower the pH. Magnesium ions are those with greater destructive power of the hydrated products of cement paste.

As already mentioned, the concrete surface erosion caused by the impact of waves, as well as temperature variations, also deteriorate this material.

4 The influence of chemical composition of concrete in the beginning of the deterioration mechanism

The deterioration mechanisms are directly or indirectly related to the chemical composition of the concrete. A suitable quality of this material, controllable by their chemical composition, influences the beginning and development of these mechanisms.

- An appropriate porosity, controllable by the ratio water/cement and the use of additions, minimizes the penetration of aggressive elements into the concrete.
- A high amount of hydroxides (carbonated substances) gives the necessary alkalinity of the concrete for the non-occurrence of carbonation process.
- A high C_3A content minimizes the penetration of chlorides [4], because they have the ability to fix these ions.
- A low C_3A content and a low ratio water/cement make the material very resistant to attack by sulfates.
- A high alkali content and reactive aggregate in concrete and the presence of water can initiate the attack of the alkali.

In conclusion, in order to ensure a resistant concrete to the exposure environment of structure, it is necessary to know the likelihood of each deterioration mechanism. Based on this knowledge, it is necessary to ensure the use of the most suitable cement to the environmental exposure of the structure.

5 Assessment and diagnostic of reinforced concrete structures

Due the durability problems that were mentioned and its consequences for the performance of the structures, it is extremely important to control and assess its integrity than can be change by the occurrence of deterioration mechanism of materials. Inspection actions and continuous monitoring of the structure are crucial in ensuring the safety of the structures. These actions allow an early detection of anomalies and prevent irreversible damages and heavy losses.

The assessment of degradation of the structures in a marine environment can be performed using the most appropriate diagnostic techniques for each deterioration mechanism. In order to ensure an accurate assessment of the weak state of the structure, should be used more than one technique of diagnosis and their results should, subsequently, be complemented [9].

There are non-destructive and destructive techniques. These last should be the last option. In fact, the integrity of the structure should be, whenever possible, ensure.

Currently, there are many techniques capable of measuring the quantity of chlorides in the concrete, as well as its pH level. It is also possible to measure the levels of conductivity and resistivity of concrete and, therefore, control the level and risk of corrosion. The integrity of the concrete, i.e., the detection of anomalies, defects and discontinuities along the structural element, can also be assessed using techniques based on the wave propagation. In order to evaluate the behaviour of the concrete, it is also possible to determine the thickness of the concrete covering layer and determine the delamination level of the concrete. Extraction cores can accomplish the determination of the resistance characteristics of this material, as well as its physical and chemical properties. This technique also allows a visual inspection of the sample and allows the realization of other tests as, for example, the determination of the depth of chlorides.

The selection of diagnostic techniques should be made in consideration of the purpose of the test and different constraints that are presents, as the state of the surface to analyse and its access. Before the selection of the techniques and any reinforcement intervention, a visual inspection to the structure is indispensable, in order to understand its behaviour, its major problems and anomalies. All the irregularities detected, as cracking and reinforcement or exposure, must be mapped and analysed [10]. A detailed and rigorous inspection of the structure allows the best choices and decisions regarding any assessment and/or intervention of the structure.

6 Case study – The Faro’s bridge

The durability of structures is a complex issue and requires special attention and concern. The Algarve has an extensive coastline and a dense atmosphere of chlorides, and it is characterized by high temperatures and moisture content [11]. This region has all the necessary conditions for the occurrence of corrosion. For these reasons, the conservation and security of a bridge in the marine environment, located in the Algarve, was assessed: the bridge that allows the access to the Faro’s beach, shown in Figure 2. It is reinforced concrete bridge with total length of 180 m [12].

Figure 2 – General view of Faro's bridge

The bridge of Faro is an old structure, with more than 50 years, where were not adopted any monitoring plan or any preventive action to the early deterioration. As such, the bridge seems a high level of degradation, with extensive cracking and some delamination of the concrete, characteristic of a strong corrosion of reinforcement. Several structural elements have also rust stains and exposed corroded reinforcement. All these characteristic show the high level of corrosion of reinforcement that occurs.

6.1 Fundamental combination of actions

The security check to the action of vertical loads requires the consideration of existing damage to the structure. Therefore, the structural elements were rated on a scale from A to E and then were applied empirical coefficient of resistance and stiffness decrease [13]. The following figures illustrate the most representative damages and their classification.

Figure 3 – Longitudinal cracking and rust stains – Level A

Figure 4 – Transversal cracking – Level B

Figure 5 – Extense delamination and rust stains – Leve C

Figure 6 – Extense delamination and exposed of reinforcement – Level D

The appearance of the bridge is worrying. However, it is concluded that all the structural elements analysed, pillars and longitudinal beams, is "loose" in relation to acting actions. The "vehicle type" is the load case that has a higher percentage of exploitation of the resistant capacity of the structural elements. In turn, the margin of safety on the road overhead is higher than the “vehicle type” because this structure are very hyperstatic, that allows a load distribution to a large number of elements That’s represent the current traffic situation.

There was predominance of positive bending moments and, in the south of bridge, the occurrence of positive moments in supports. This situation indicates the inability of the soil to resist the action that is transmitted to it, due not only because of the poor quality of the soil foundation, as well as the reduced depth of spiking pillar-cutting. It is a settlement of support.

6.2 Seismic combination actions

First, it should be noted that the structure in question was not designed to the occurance of a seism. However, the bridge is located in a high seismicity zone and it is very important to analyse your response this action.

In the event of a seism, it is the shorter pillars the first to yield. Indeed, these elements only resist to low intensity seismic action: 14% for the longitudinal seism and 54% for the transversal seism. The rest of the structure has an average capacity to resist to 70% for the longitudinal seism and to resist to 100% for transversal seism. The short pillars mainly condition the resistance of structures. The poor resistance of these pillars it’s because to its short height, being more rigid elements and having higher efforts.

Figure 7 and Figure 8 shows the interaction curves for the spring pillars, for longitudinal and transverse seismic respectively.

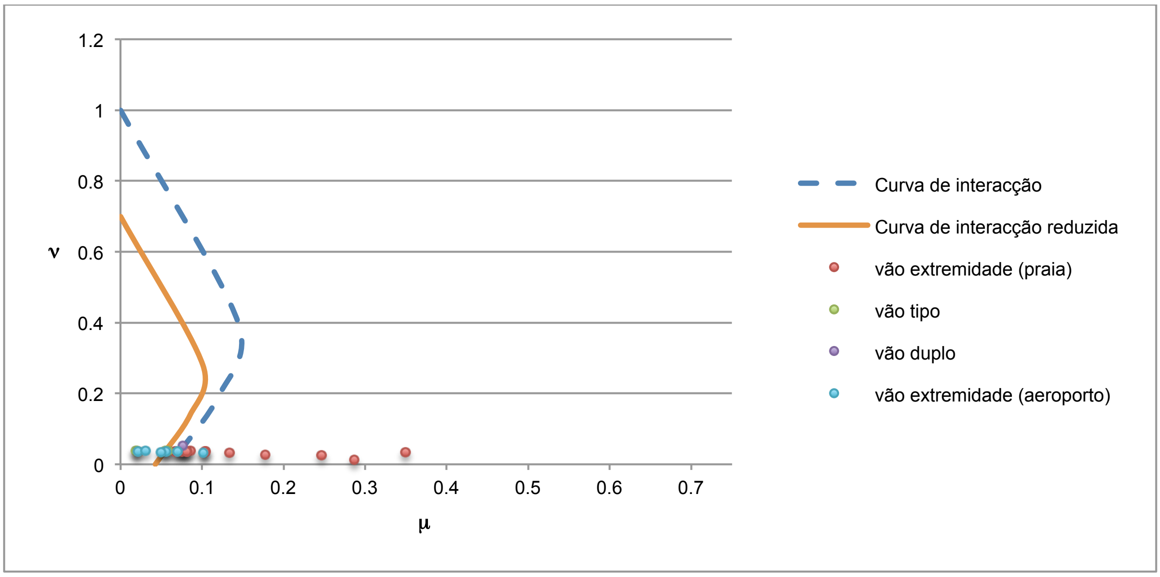

Figure 7 – Interaction curve N-M: longitudinal seism

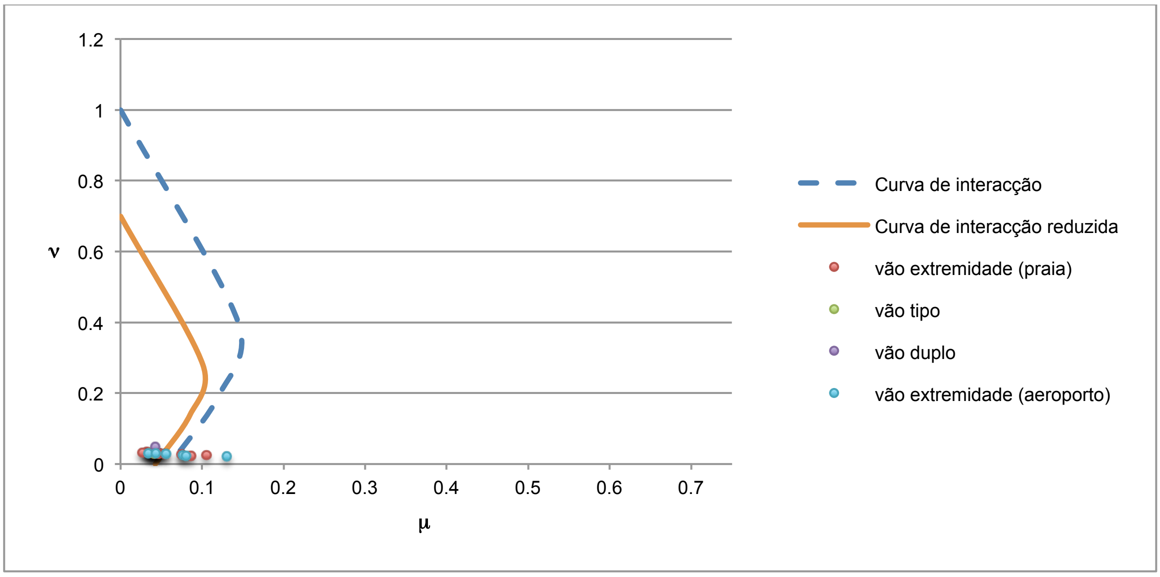

Figure 8 – Interaction curve N-M: transversal seism

The analysis of these figures shows that the longitudinal seism is more severe than the transverse seism. There is also verified that the pillars has very distinct behaviours, during the occurrence of these seisms. In fact, the longitudinal stiffness is much higher than the transversal stiffness. The longitudinal stiffness is also asymmetrical along the length of the bridge, unlike the transverse stiffness, which is very similar in all alignments pillars. It is for these reasons that the longitudinal seism originates higher efforts on pillars, compared with the transverse seism

7 Possible interventions

The pillars have different answers to the action of seism. A possible intervention in these elements should be differentiated, according to the distinctive request of these elements to seism.

The strengthening the structure to 100% of the regulatory seismic action is not viable, because it is an old structure with a low importance. This solution required a severe intervention of structure. Therefore, it is suggested to strengthen the extreme pillars to 50% of regulatory seism that is equivalent to a "service" seism, for new structures, with a probability of 10% in 10 years.

For this action level, only the extreme pillars need to be strengthened. In fact, they are the most critical elements.

Reinforcing a pillar can individually carried by a casing solution. However, the first extreme pillars have a very reduced height, require a large increment of resistance and are difficult to access. Because of that, a solution by placing diagonally arranged metal profiles, may be more effective and viable. This solution allows to reduce by 90% the bending efforts and displacements.

This solution is illustrated in Figure 9.

Figure 9 – Bracing solution

It is suggested, therefore, a brace in the most critical solution of pillars (P1 to P4 alignments) and a casing solution in the remaining reinforcing pillars.

Equally important, the enhanced approach to foundations should be considered in order to be mobilized stiffer soil. In fact, soil-structure interaction response is reflected in the response to the actuating action of the superstructure.

Has not been analysed, the high state of degradation noticed the locking beams can also compromise the safety of the structure. These elements have the ability to reduce the bending efforts of the pillars and give more transversal and longitudinal stiffness to the structure.

8 Conclusions

The durability of concrete structures has an extremely importance in designing structures. Repair costs due the early deterioration of the structures are expensive and exceed many times the initial cost of the structure. The marine environment is a very hazardous environment for concrete structures because it has the ideal conditions for the occurrence of corrosive mechanism.

There is a strong interaction between the structure and its exposed environment, because the elements in the atmosphere react with the constituents of concrete, causing deterioration of the structure. If preventive measures to deterioration are adopted, this phenomenon can be delayed and minimized. The concrete chemical composition must be appropriate to the exposure environment in order to give the greatest possible resistance to exposure conditions. A knowing the environmental conditions of the structure, deterioration mechanisms that has higher probability of occurrence and the adoption of preventive measures at the level of the materials, can ensure the quality and the resistance appropriates to reinforced concrete structures in marine environments.

The Algarve has all the ideal condition to start of corrosion mechanisms: the presence of chlorides, high temperatures and moisture levels. Therefore, the assessment of the condition and safety of the structures located here, as is the case of Faro's bridge, is important. The main degradation mechanism is the action of chlorides.

This bridge old bridge has a high level of deterioration. However, security of structural elements to the action of the vertical loads is verified, because this is a very hyperstatic structures and there is a distribution of effort by a large number of elements.

This structure has not been designed to the action of earthquake. As such, it is only ensured non-collapse for 14% of the longitudinal seism and 54% of transversal seism. The shorter pillars have more stiffness than the other and, for that reason, have a very high stresses and require further strengthening. Ensuring the security of 100% of the earthquake bridge is not a viable solution because it requires a severe intervention in all structural elements. This is an old bridge with a little importance, so it is suggested strengthening to 50% of seism.

The reinforcement of the pillars can be made through a solution of casing or a bracing solution. This last allows a reduction of about 90% of efforts and displacements. It suggested the implementation of these two solutions.

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