Durability of prestressed concrete structures in a maritime environment – Case Study

Extended Abstract

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1. Introduction

The aim of the following work is to characterize the condition of a prestressed quay-bridge, regarding corrosion related issues, which has been in service in a maritime environment.

Corrosion is an electrochemical process during which the steal elements, such as the reinforcement or the prestress cables, are gradually dissolved. Given that, this phenome cannot develop in an alkaline environment, elements are generally protected by the alkalinity of the surrounding concrete, which generates a thin layer on the surface of the steal elements. When the described situation occurs, the elements are told to be protected by passivation, but since the moment when this layer is destroyed the availability of oxygen and moisture is enough for corrosion to develop.

One of the most harmful ways for this layer to be destroyed is the contamination of the concrete by chloride ions. Above a certain critical content the reinforcement is considered to be despassivated and corrosion might develop when the previous conditions are verified. The previous reasons make the maritime environment one of the most aggressive for the reinforced and prestressed structures, given that it's rich in chloride ions, which lead to despassivation, and provides the main remaining elements, moisture and oxygen, for corrosion to develop.

The described issues are particularly worrying in prestressed structures, given that rupture might occur without any previous warning. Therefore, it is crucial that construction details, regarding the durability of the structure, are carefully executed. Besides that, monitoring assumes a crucial role preventing this type of incident. Unfortunately the available methods of direct observation of the cables are too intrusive, causing serious damage when applied over large areas. Other techniques with the aim of assessing the state of the cables have been developed, over the years, but none of them provides reliable information about the full length of the strands. Moreover, most of them can only be applied under considerably favorable conditions.

Based on these facts, the demolishment of the quay-bridge in question constitutes a rare opportunity for the direct observation of prestressed elements that have been serving in an aggressive environment. This type of intervention is not common on this type of solution, given that those have, generally, considerable dimensions and are projected for a long life-cycle.

The referred structure takes place on the Lisnave dockyard, in Setúbal, and has shown several corrosion related issues over the years. The approach to the case-study will be made in three major stages, starting with the visual inspection of the elements removed and the corresponding photographic survey. Then, samples of the strands will be collected and submitted to a tensile test, to assess their current mechanical properties. Finally, a chloride content test will be conducted over samples of the grout and of the cables surrounding concrete.

2. The corrosion

Corrosion is the electrochemical process that leads to the dissolution of steal and, therefore, the disintegration of the reinforcement.

The first requirement for corrosion to occur is the despassivation of the steal. Under normal conditions, the alkalinity of concrete forms a thin layer on the reinforcement surface that avoids the development of the corrosion process, when that is the case, steal is said to be protected by passivation.

There are two major mechanisms through which this protection can be destroyed, those are the carbonation and the contamination by chloride ions. Carbonation occurs when the carbon dioxide reacts with the calcium hydroxide, responsible for the concrete alkalinity.

The second mechanism develops when a critical content of chloride ions is exceeded. These ions are present in the sea water and penetrate in the concrete structure through partially or totally water filled pores, and the damage of the passive layer is mostly localized.

The corrosion process implies the establishment of an electrical current and can be described by two main reactions, the anodic and the cathodic. The circuit establishment also requires and electrolyte, which is the water present in the pores, and a conductor, which is the reinforcement itself.

In the anode the iron is dissolved by the reaction:

$$Fe \rightarrow Fe^{2+} + 2e^{-}$$

While in the cathode, the two electron released are combined with water and oxygen, through the following reaction:

$$2e^{-} + \frac{1}{2}O_2 + H_2O \rightarrow 2(OH)^{-}$$

After some other intermediate reactions the two hydroxide ions react with the iron ions released in the anode to form the iron oxide, regularly called rust. This product is formed with an expansion in volume that ultimately leads to severe damage in the surrounding concrete.

The development of the corrosion mechanisms requires the presence of both water and oxygen, so it cannot occur neither in saturated concrete or in dry conditions. The areas with the highest risk, regarding this type of deterioration, are those that are subjected to wetting periods and drying periods.

The anodic reaction requires the passive layer to be destroyed, but the cathodic reaction can occur even if the passive layer is intact. In the case of the contamination by chloride ions, the passive layer is locally, generating confined anodic areas, while the cathodic process can be occurring over a long portion of the strand. The need to balance the current generated in both processes leads to a great loss of section in the anodic area, which generates localized corrosion.

In a maritime environment, the area that is considered to be the most vulnerable for corrosion to develop is the one above the high tide, where the structure is constantly pulverized by sea water. Despite the fact that the intertidal zone is subjected to wetting and drying periods, the periods during which the structure is submerged are enough to keep the concrete saturated all the time, leading to low corrosion level.

The process of deterioration by corrosion in presretessed structures, develops the same way as it happens in reinforced concrete structures. Despite that fact, there are a number of reasons that make prestressed structures require a much more careful analysis regarding this topic. First of all, these type of solution works under tensions much closer from their rupture point and their rupture mechanism is generated with, approximately, no deformation, which makes it very difficult to predict. Moreover, the strands, affected by deterioration, have a much smaller diameter, when compared with the regular reinforcement, so that a small depth of corrosion will lead to a significant loss in cross-section area.

The described facts make a prestressed structure sudden collapse very hard to predict, assuming the constant monitoring and a perfect design and execution a vital role for this constructions safety.

The inspection programs that have been carried out in some countries, where bridges with this type of solution were starting to display corrosion related issues, revealed that most of the problems observed were due to poor design or execution. From those problems, the majority had to do with the correct injection of the grout inside the ducts, given that there was relatively common the presence of voids inside the ducts.

The observations generated a series of improvements related with the formation of specialized workers to apply this kind of technology, and most restrict regulations regarding the materials used and the way they should be operated. One of the most relevant techniques that emerged, with the aim of solving the injection problems, was a vacuum creation technique in which vacuum is generated on one end of the duct and the grout is pumped from the opposite end, the combination of both effects prevents the presence of voids and makes the process become much faster.

Another strong limitation, regarding the assurance of an adequate durability, is that the non-intrusive methods of monitoring the cables often do not provide realistic results or, at least, not for all the cable length. Most of them depend on the verification of almost ideal conditions to provide useful information, for instance, the magnetic or the georadar method generate misleading results when there are other steal elements in the proximity of the cables. Another example is the radiographic method, which has revealed to be too expensive and harmful for the populations, requiring the evacuation of people in the surrounding land.

The most reliable method of inspection is still to carefully open a cable and visually assess the state of the strands. This also provides the opportunity of collecting samples for laboratory analysis, but requires the detailed planning of the reparation operations afterwards. Even more relevant is the fact that this method is applied in a very precise location, requiring the existence of a suspicion that a cable is developing problems in a certain location.

In the recent years a technology has been developed, in Switzerland, that contemplates electrically isolated cables with thick plastic ducts. This has been applied with success in several cases, and is particularly suitable for inaccessible elements, given that it allows the assessment of the chemical stability of the element by measuring his electrical resistance.

In terms of the design and execution practices, is actually recommended the use of a multi-layer protection based on the principle that if one of the layers is intact the structure is protected. In the case of internal cables, is also recommended the use of non-metallic ducts, given that these, not only provides protection against corrosion, but also make possible the use of non-intrusive monitoring methods, such as the radar.

A more careful planning of the elements that have the highest risk of chlorides ingress, such as anchorages and joints, is also crucial. For instance, a construction joint should never be placed near an anchorage or a duct joint. The ingress of water in the structure must as well be avoided through the adoption of suitable waterproofing systems, that constitute the first layer of the multi-layer system. The recent liquid membranes have proved themselves to be more efficient than the traditional systems.

Regarding the improvement of the concrete cover, the possibilities are to increment the thickness of cover or to reduce the porosity of the concrete. The second one is more adequate because it does not increment the weight of the structure. The lower porosity can be accomplished through the use of additives, replacing a percentage of the cement, that also reduce the hydration heating.

It is important to mention that, in the case of constructions inserted in a particularly aggressive environment, special measures of protection can be necessary and each particular case must be individually analyzed.

3. **Case-study**

The case-study which is the object of the present work is the demolition of a quay-bridge, located in Setúbal, in the Lisnave dockyard. The rfered structure has always presented problems related with corrosion because it is serving in a maritime environment, which is extremely aggressive regarding this type of deterioration, and has been projected in a time when this phenomenon was not fully understood. The particular interest of this intervention is due to the fact that it is not common for a prestressed structure, which is intended to serve for a very long period, to be demolished. Therefore, it constitutes a rare opportunity for the direct observation of the issues revealed by the structural elements that have been serving in such an aggressive environment.

The structural system is composed by 5 spans over which a reinforced concrete slab, with transverse prestress, is supported by 6 longitudinally prestressed beams. In every beam, there is a cable, placed close to the lower surface of the slab, that does not have a structural role in service but whose utility is related with the construction phase, during which the beams are only supporting their own weight, making the amount of prestress exaggerated. This cable, which we will call superior cable, as the function to annul this effect, particularly the tractions generated in the superior portion of the beams.

An earlier inspection had already been carried out in 1995, and some major concerns had emerged regarding the deterioration status of the bridge.

The bridge that is the object of the study is part of a group of three similar bridges. By the time of this inspection, a laboratory chloride test was conducted over samples of one of the other bridges revealing a content way above the limit established by the regulations.

By that time it was concluded that the issues revealed in were due to inefficiencies in the project, such as the quality of the concrete preconized and the insufficient thickness of the concrete cover, and inefficiencies in the execution, such as the use of a concrete with inferior quality than the preconized that was poorly applied and compacted, presenting considerable porosity. These facts combined with the very aggressive surrounding environment led to the deterioration observed.

Nowadays, demolishment was considered to be the best option given that the referred issues were aggravated and the structural safety could be threatened. The fact that the structural elements were mostly prestressed, with high corrosion sensitivity, and that the accurate assessment of the deterioration of the strands was not viable, made this the most reasonable decision.

It was established that the demolishment process was to start from south to north. In each span the slab would be sectioned, using the cutting disc technique, to individualize the portions of beam to retire, and holes would be opened so that the beam could be tied with the cables of the crane. After this, the barge that carries the crane, and that will carry the beams to the deposit, is placed close to the beam to demolish, than the beam is tied with the cables to be cut in to sections, using the cutting wire.

There are to major factors that affect the rhythm of the operation, which are the load capacity of the barge and the tides. The beams can only be tied with the cables during a low tide and can only be taken from the barge, at the deposit area, during a high tide. These two particular factors are therefore crucial to be managed with the aim of making the operation as fast as possible.

The new platform will be constructed with a similar structural system but with special care regarding the prevention of corrosion related issues. The slab will no longer contain the transversal prestress. The beams will be produced in controlled conditions, with a high performance concrete regarding the penetration of chlorides, with a thicker concrete cover and a superficial protection. New polyethylene ducts will also be adopted. In terms of design, the major difference is that the beams will be projected to allow access to their top section, where the anchorages are located, for future inspections and eventual maintenance operations.

With the aim of characterizing the deterioration status of the quay-bridge, an approach was established to follow the demolishment process. The main tool, for this purpose, would be the direct observation of the elements, accompanied by a photographic survey, to register all the anomalies. It was also established that each beam would be photographed starting at the north section, than west side, south, and finally south. This was intended to prevent any mistake while, posteriorly, analyzing the photos.

The second tool to the analysis would be the collection of samples, from the cables surrounding concrete and from the grout inside the ducts, over which a chloride content test should be conducted. A drill would be used to collect these samples which requires electricity and forces this operation to be performed only on the barge.

Finally, samples of the strands would be collected, from the deposit area, and tensile tests would be performed over them, to assess their current mechanical properties.

4. **Demolishment attendance and anomalies observed**

At this stage it is intended to register any issue that can be attributed to the development of corrosion phenomenon. The major problems that were expected to be found were the corrosion of reinforcement, ducts or even, is the most advanced cases, strands, and also problems related with the formation of the corrosion products, such as the cracking or the delamination of the surrounding concrete.

These anomalies should be registered photographically and also in schemes of the beams, with references to the length of the damage observed. Based on the referred elements, conclusions were intended to be taken about the general status of deterioration of the quay-bridge and about its capacity to still perform how it was expected to.

After the particular analysis of each beam, the general analysis was made and several conclusions could be taken. The most common issue, that occurs in approximately every beam, is the deterioration of the superior cable, the concrete in this zone is not saturated, because this one is located above the high tide level, generating ideal conditions for corrosion to develop. In most of the cases the duct was already corroded, showing that the concrete was not playing its protective role, and in the most serious cases it had already been disintegrated and the strands were exposed and deteriorated.

This deterioration of the superior cable usually generates problems of concrete loss in the beams' webs, due to the expansive reactions associated with the corrosion products. This situation always occurs in the zone that is closer to the supports, where the load applied to the webs by shear force is more relevant, which leads to serious concern about the capacity of the beams. The fact that this damage is more concentrated near the support is due to the fact that the shear force generates a proportional longitudinal tension, on the webs, that combined with the tensions generated by the expansive reactions leads to the referred damage to develop.

In some cases, mainly at the span which is closer to land, it is observed a contrast between two different types of concrete, what reveals a previous maintenance operation, the cracks tend to develop between the two types of concrete generating huge loss of concrete. The referred span is generally the most damaged due to two factors, the first one is that the fact that it is located closer to the dockyard has made it much more loaded during its lifecycle, the second, and most relevant, is that the proximity to the dockyard creates a micro-environment given that the waves hitting the dock generate a more frequent pulverization of the concrete with sea water.

Another situation that is very often verified is the delamination of the inferior surface of the slab in the area located at mid span, between the two crossbeams. This delamination also occurs in other places of the slab although much less frequently. The fact that the mid span zone is more susceptible to this is due to a micro-environment, in which the agitation of the water constantly pulverizes the slab with chloride contaminated sea water, while closer to the supports this agitation does not exist due to the presence of those supports that work as a barrier.

In two cases there were cables, in the crossbeams, that had not been injected with the grout. This reveals that in some cases poor execution might also have been a problem.

5. **Strands tensile test**

At this stage tensile testes were to be performed over the strands samples collected on the deposit area. The goal was to establish a relationship between the type of damage presented by each strand and its response to the test. It would also be interesting to verify if its response was similar to that of a sane strand. The strands originally had a 7 millimeter diameter and were constituted by steal 1670/1860.

The strands were selected for the test and then had to be cleaned from the rust accumulated on the surface. There were chosen 3 reference strands in good conditions, to simulate the response of a sane strand, and 8 damaged strands to run the tests. For the extension measurement it would be important to predict the place where the rupture would occur. It was also crucial to approximately determine the area of that section, so that the force values given by the test were converted to stress.

The expected tension of collapse for this type of steal would be 1860 MPa and, according to the regulations, the prestress steal should guaranty at least 3,5% extension when the collapse occurs.

After running the tests, the following results were obtained:

	D (mm)	Área (mm^2)	Frot (kN)	σ (MPa)	ε (%)
R1	7,07	39,2580	67,71	1724,74	4,2554
R2	7,09	39,4805	68,14	1725,92	5,7898
R3	7,08	39,3692	67,32	1709,97	5,6184
D1A	-	37,2262	58,71	1577,12	2,0506
D1B	-	36,9132	65,31	1769,29	4,7292
D2A	-	33,2231	55,32	1665,11	4,0870
D3A	-	33,4049	51,5	1541,69	2,0222
D3B	-	36,4376	61,75	1694,68	4,1910
D4A	-	37,8512	64,07	1692,68	-
D4AA		37,8512	63,37	1674,19	-

D5A	-	24,2652	31,52	1298,98	0,9300

The most relevant conclusion that we can take from these results is that three of the samples do not verify the minimum extension required. These samples are D1A, D3A e D5A. The D5A sample has to be analyzed individually, as it is much more damaged than the remaining samples, but regarding the other two samples, we can see that, despite a similar cross section loss, the collapse occurs at a lower tension and, especially, with a much lower extension.

What these two samples have in common is the fact that the damaged is concentrated on a small length, surrounding the rupture section. In those samples where the damaged is distributed over the full length, the loss of resistance is smaller and the extension verified when the collapse occurs is well above the minimum required.

Based on the above, the main conclusions that we can take are that concentrated deterioration is much more harmful to the mechanical properties of the steal elements, and especially harmful in what concerns to the deformation capacity. This type of deterioration is usually associated with the corrosion mechanisms generated by chloride contamination, due to the small anodes that are formed.

The kind of environment in which the structure has been inserted is rich in this type of elements and, therefore, this kind of deterioration is fairly common. The D5A sample, which was severely damaged and very far from meeting the safety requirements, can be associated with some cases observed during the demolishment of the quay-bridge, where the strands were exposed, showing that in these cases the elements were already very far from the mechanical properties to which the structure was projected and that the collapse could be eminent.

6. Chloride content assessment

The chloride content assessment was performed using the Rapid Chloride Test (RCT), in which the chloride content in a concrete sample is estimated by using an electrode and a calibration curve, to convert the readings, in mV, to a percentage of chloride ions.

The referred calibration curve is obtained by measuring the voltage in four standard substances, with a growing chloride concentration of 0,01%, 0,03%, 0,05% and 0,5%, and then calculating the equations of such curve. These readings are made at the beginning and in the end of the experiment, and the average values are used to obtain the curve, in order to prevent that a sudden change, in the conditions of the test, from leading to fallacious results.

Afterwards, the samples of concrete and grout were prepared to be tested, using the same procedure, by mixing 1,5 grams of the sample powder with 1,5ml of nitric acid and 50ml of destilled water, then the blend was vibrated for a few minutes and filtered into a test cup. The group of tests performed was constituted by a sample of grout and a sample of concrete from the beams V4.1, V5.1 and V5.2. The results were the following:

		Ataque 1 (mV)	**Ataque 2 (mV)**	**Média (mV)**	**%** Cl^{-}
V5.1	Betão	163,2	163,4	163,3	0,082
	Calda	226	291,4	258,7	0,000
V5.2	Betão	166,6	158,7	162,65	0,085
	Calda	225,7	225,3	225,5	0,003
V4.1	Betão	166,5	166,4	166,45	0,069
	Calda	200,9	204,7	202,8	0,013

From such results we can immediately confirm that a higher chloride contamination will lead to a lower resistivity and, therefore, to a higher corrosion rate.

The critical chloride content for a sample of concrete that has already been in service is considered to be 0,2% of the cement mass. The cement content in this particular concrete is around 300kg/m^3, which leads to 0,024% of the concrete mass. The chloride content of the concrete, collected from the surroundings of a pre-stress cable, clearly exceeds the critical value. This justifies the deterioration observed in most of the metallic ducts, that were already being corroded due to the depassivation of the concrete cover. The very low content, revealed by the samples of grout, demonstrate that the strands were still being protected by metallic ducts but it would be a matter of time until that this one was disintegrated. This evidence is supported by the damaged strands collected in some locations where the ducts had been destroyed by localized focus of corrosion, a typical pattern in chloride contaminated environments.

7. Final considerations

Despite a few limitations regarding the approach of the case-study, that did not allowed the study to be as detailed as it was predicted in some points, the major objectives were accomplished. The complete assessment of the case-study has been performed and it was possible to confirm the theoretical knowledge, acquired during the bibliographic research, with the observations made and the laboratory tests. Even more interesting was to observe the influence of some extra factors on the deterioration pattern, such as the micro-environments created in a structure of this dimension.