Inspection, evaluation and rehabilitation of steel bridges

Mariana Cardoso Marques
marianacardmarq@gmail.com
IST - Technical University of Lisbon, Portugal
October 2019

Abstract: Most metal bridges have been in use since the 19th century. From its construction to the present day, signs of degradation are visible due to age and factors that accelerate the deterioration process. If maintenance, rehabilitation and/or replacement measures aren't taken, structures may no longer be safe to perform their function. Due to high built heritage, there is an increasing change in policies, with a consequent increase of rehabilitation opposing to new constructions. However, to be cost effective, rehabilitation of works of art requires maintenance which is only possible with national policies for existing heritage preservation, including periodic inspection actions. The accuracy of the intervention plan depends on the diagnosis and evaluation of the artwork. It's essential to establish standards and define strategies to standardize the execution and procedures to be performed by the inspection team. Inspection deadlines and report typology are referred to in the IP artwork management system in the SGOA. However, maturity in the selection of the materials, structure testing method and the choice of repair methods, according to the detected anomalies, is needed in the decision support tool. This dissertation deals with the evolution of structural solutions and materials; summarizes tests to be carried out in order to evaluate the materials and the condition of the structure; inspection procedures; and rehabilitation solutions for some of the most common anomalies. The main objective is the definition of a methodology to carry out an inspection action, from the analysis of the anamnesis of the structure to the necessary intervention. To this end, various international and national standards were consulted, and their procedures were adapted to the Portuguese reality.

Keywords: steel bridges; rehabilitation; inspection; evaluation; material testing.

1. Introduction

The need for mobility is inherent to the social and economic activities of the human being, however there are certain natural and artificial obstacles that condition this mobility, leading to the construction of bridges and viaducts. The construction of metal bridges is cost-effective as it combines strength, ductility, ease of fabrication and accelerated construction. These works of art generally have high durability if properly maintained, but problems such as corrosion, fatigue, deformation and anomalies in joints must be identified and resolved to maintain the safety and functionality of the structure. To assist the management of existing heritage and to verify and schedule intervention needs there are systems of management of works of art.

1.1. Objectives and Methodology

The main goal of this research is to contribute to the systematization of all stages of conservation of the rail and road metal bridges in Portugal. Currently, there is a management system for works of art. However, in this system there are procedures that are not regulated, allowing subjectivity in the process. To fill this gap, these processes are identified and the procedures to be adopted are systematized, namely the material characterization tests, the inspection steps, the structure components conservation state characterization tests and the repair methods in the face of the identified anomalies. In order to verify that the systematized procedures are adequate, they will be applied to two case studies that consist of two bridges that required inspection and rehabilitation actions.

2. Evolution on steel bridge construction

2.1. Evolution of materials

Iron begins to be extracted from the meteors [1], however, because it reacts with oxygen, it doesn't appear in nature in its pure state. Cast iron results from the burning of coal and consequent release of carbon monoxide that reacts with iron oxide and produces pure iron in the reaction products [2]. This material has carbon percentages around 2% and, therefore, is not weldable. Because it contains phosphorus it has a fragile behavior that is reflected in low tensile strength values (131N/mm2) [3]. With Henry Cort's process of puddling, it was possible to reduce the percentage of carbon to below 0.08%, originating wrought iron. This material has better tensile strength with characteristic yield and ultimate tensile stress values of 228N/mm^2 and 372N/mm^2, respectively [3].

2.2. Structure typologies

Due to their low self-weight ratio and strength, steel bridges have a lot of structural diversity which can be grouped by type of use, geometry, structural shape, slab type, cross section, deck position and construction process. According to report 366 (2010) of Laboratório Nacional de Engenharia Civil (LNEC) [4] the bridges can be divided into distinct groups according to their structural solution:

- Arched Bridges: this structure typology can work with the upper deck, such as the Coalbrookdale Bridge (1779), or lower-deck arching bridges, such as the Hohenzollern Bridge (1910). This structural system has a similar behavior than a truss.
- Suspended bridges: The vertical cables that suspend the tray transmit the load to the main cables and these cables transmit the forces to the piers. Nowadays these types of bridges are mostly in steel due to their high ratio strength-weight.
- Girder bridges: with the need for a rail link between London and the Isle of Anglesey, a bridge with a rectangular tubular geometry designed by Stephenson emerges in 1844. This pioneering wrought iron bridge was built to face a span of 142m and consisted of composite beams with spaced reinforcements.
- Console bridges: the construction of continuous beams instead of simply supported single spans allows the reduction of efforts and deflections. This construction is based on increasing the height of the beam on the columns, making it possible to construct cantilever for the span without the need for shoring.

2.3. Connection between metallic elements

Although small in comparison to the rest of the structure, the metal connections are important in terms of the structure's operation and economic impact. Bonding techniques have evolved following the modification of materials. The oldest steel bridges are riveted due to their rigidity and strength characteristics. This riveting technique, which aims to permanently and rigidly connect two individual pieces, requires a lot of labor that was not so expensive in the past [5]. Due to the economic appreciation of the skilled workforce in the 20th century, this technique is no longer economically competitive. Thus, in current interventions, if the elements to be replaced are numerous and there is no constraint on the preservation of historical heritage or structural impediment, the intervention may involve replacing the rivets with bolted connections. Screws are connectors that have the advantage of being reversible connections and can be applied by various systems. Currently, the screws can be normal, adjusted, high strength and complemented with resin injection [6]. In current structures the most used technique is welding, which consists on heating the ends of the two pieces to be joined up to melting point, allowing them to solidify together, ensuring that there is no discontinuity between them. This procedure is also an option for repairing damaged riveted connections, however, it is common to have some incompatibilities, notably with existing materials and the environmental conditions on the area of intervention.

3. Material characterization tests

Evaluating the structure implies knowing the materials that constitute it and, if this information does not exist, is insufficient or dubious, tests that define the characteristics of the materials should be requested. According to Joint Research Center (JRC) in 2008 [7] the number of trials requested depends on the information available (Table 1).

Table 1: Number of sampling

Obtained information	Samples	Tensile test	Chemical analysis	Fracture mech. test	Note
The information is known and is validated.	0	0	0	0	-
All members are from the same material, but there are some doubts about the information.	3	6	1	3	random sampling-
The members of a structure are made of different steel and there are some doubts about the properties of the structure	1 per member	2 per sample	1 per sample	1 per sample	random sampling-
Lack of obtained information or information available probably wrong.	≥ 3 per member	2 per sample	1 per sample	1 per sample	random sampling-

3.1. Chemical characterization and weldability

These tests aim to evaluate the carbon, silicon, manganese, phosphorus, sulfur and nitrogen contents in the material under analysis, as these elements interfere with its behavior. For example, high carbon levels lead to hardening of the steel, which in turn causes loss of ductility [7]. In addition to chemical analysis to determine the content of the mentioned elements, there are other methods to identify the type of material under study, such as spectroscopy techniques (quantitative and qualitative analysis) and metallography (qualitative analysis).

3.2. Weldability tests

After determining the chemical constitution of the material, it is possible to estimate the metal production process and verify its weldability. However, the determination of the weldability of a metal can begin with the *in situ* investigation of the presence of welded joints made at the time of manufacture and assembly on site. A quick test may be carried out to verify the welding behavior: a weldable part is welded to an element of the structure to be evaluated and a dry blow is performed with a hammer. If it deforms without fracturing, the material is weldable. However, if the weld separates from the metal in the bonding zone, it means that the metal is hardened and, therefore, not weldable [7].

3.3. Mechanical characterization

The chemical composition has a key impact on the behavior of a metal, however, tests may be performed to evaluate mechanical characteristics, namely, limit values of elasticity, tensile strength and fracture toughness. One of the most common tests to evaluate metal strength is the tensile test regulated by EN10002. In this test, the specimen of defined geometry is subjected to an increasing tensile force, generally to its rupture, and is elongations over time as a function of applied force are measured [8]. The results of this test are generally presented as stress-strain graphs. Shock tests also allow to evaluate the susceptibility of fragile fracture occurrence [8]. The underlying mechanism is to determine the energy expended in deforming and breaking the specimen through an impact. The Charpy test is the most recurring shock test and is regulated by ISO148:2016. Release of the test equipment impactor from an established height allows the known potential energy to be converted into kinetic energy. Part of this energy will be absorbed by the specimen with which the pendulum intersects during descent. After impact, the impact angle of the pendulum is measured, allowing to determine the energy absorbed in the fracture of the specimen plus friction losses, deformation and dynamic response of the equipment [8]. For structures that are subjected to cyclic loads, such as bridges, it is important to realize that the collapse of elements or the entire structure can occur at stresses lower than those causing breakage in static stresses. This fatigue phenomenon is initiated by the opening of a propagating micro-gap forming a crack in the direction of the cutting plane due to cyclic stresses [9] and the test of this phenomenon consists in subjecting a specimen to a tension below rupture and subject it to a high number of cycles.

4. Inspection and evaluation of steel bridges

The information to be gathered on the structure under consideration should be as complete and detailed as possible in order to ease the understanding of its behavior. This knowledge is also crucial for intervention to be as appropriate and as effective as possible. Design drawings and calculations, in situ measurements, laboratory material testing and non-destructive in situ testing carried out during inspection should be considered [7].

4.1. Inspection

Initially, the first assessment to be carried out is called a basic or routine inspection. Routine inspection is a regularly scheduled, usually annual, inspection, consisting of observations and any measurements necessary to determine the physical and functional condition of the bridge; identify any change in initial conditions or those recorded in prior inspections and ensure that the structure continues to meet current service requirements. After analyzing this information, a report is made containing the mapping of anomalies found, request for further analysis, recommendations for future inspections and possible repairs. These anomalies can be existence of corrosion in metallic elements; corrosion of connections; paint deterioration; bar buckling; cracks in the connections; among other defects that are visually identifiable [7]. If an anomaly is found or suspected, further investigation may be required. This is where the main or detailed inspections are given, which should take place every three years [10]. During this inspection, if necessary, test plans are defined based on the anomalies found. The most requested tests are those that provide information about the materials and connections between bridging elements that are generally not known.

4.2. Maintenance and conservation status assessment

Steel and iron are materials likely to develop corrosion phenomena. The presence of oxygen and moisture are essential factors for the occurrence of this phenomenon, which is enhanced by coastal environments due to the presence of chloride ions [11]. The areas most affected by corrosion are places of water and debris accumulation, condensation or susceptible areas where the corrosion process is aggravated by microbiological action [10]. This phenomenon constitutes a risk factor for the structure since, by causing loss of section of the element, it may compromise its integrity and consequent function [12]. Metal bridges are also subject to the appearance of cracks in their elements which may be caused by sizing, fabrication, construction and exposure over their service life. This last factor may include overload, self-weight, vehicle impact and thermal actions [12]. It may also be the case that there is improper use of the structure, namely with the loading of the structure higher than considered in the design. This phenomenon can lead to deformation (if material has ductility), brittle rupture or warping of the elements [13].

4.3. Non destructive testing (NDT)

When identifying defects in the structure there may be a need to strengthen the analysis to determine the correct location and extent of damage [13]. It is because of this need that non-destructive testing arises. These tests are useful for detecting thickness losses due to corrosion which may lead to loss of strength or rupture of the structure joints. Non-destructive methods can be grouped according to their ability to search for external or internal defects [12]. However, some allow the detection of surface and subsurface cracks. The most common methods are: radiographic, ultrasonic, infrared thermography, acoustic emission, currents of

Eddy / Foucault, magnetoscopy and penetrating liquids. The last three tests are typically considered as external / superficial methods, while radiographic, thermographic and ultrasonic tests are directed to subsurface analysis and may also detect surface defects. Acoustic emission is based on the slit's dynamic activity to detect and locate it [12]. According to [7], [10], [12] and [13] the principle of testing is:

- Eddy / Foucault currents: this technique is based on the use of induced electromagnetism to detect discontinuities in conductive materials. This is possible since defects are identified when induced electric currents are distorted.
- Radiographic: X-ray or Gamma radiation is used because of its ability to traverse materials. This radiation is absorbed to produce a high contrast image. Discontinuity zones are identified by darker colored zones.
- Ultrasonic: is based on the use of high frequency sound waves and their reflection and diffraction under material discontinuities.
- Infrared Thermography: this method is based on the fact that cracks and corrosive elements have temperature variations.
- Acoustic Emission: the sudden movement of materials under tension produces acoustic emissions which, having characteristic frequencies, can be read by sensors. These sensors monitor, collect, filter and analyze data.
- Magnetoscopy: in the execution of this test the steel surface is magnetized and small phosphorescent iron particles are applied to it. These particles are attracted by the discontinuity in the magnetic field that the defects cause, thus identifying the location of the cracks.
- Dye penetrant: penetrating liquid is applied to the surface under analysis and subsequently absorbed by capillarity thereby identifying the location of the cracks. The absorption process takes about thirty minutes before the results can be analyzed. Slits are identified by a continuous or broken line on the surface of the element.

4.4. Management system of steel bridges

Management systems regulate inspections and usually consist of three basic modules [14]: database; inspection and evaluation; decision support and management. The database contains the inventory of the bridges that are part of the network, geometric information about each one of them and the data resulting from each inspection and intervention performed. It may also contain data analysis capabilities that allow classifying anomalies by the associated risk level and assess the costs and benefits of preservation, risk mitigation and replacement activities. Recent innovations make it possible to assess these factors based not only on cost but also on issues such as safety, mobility and environmental sustainability [15].

These works of art management systems are currently managed by major national network management bodies. It should be noted that the Portuguese and European regulations are very detailed with regard to the design and sizing of structures, however, practically silent on the definition of maintenance and management standards [14]. In Portugal, with Decree-Law No. 91/2015 of May 29th, Infraestruturas de Portugal, SA (IP) was created, and this entity is responsible for the conception, project, financing, conservation, exploration, requalification, enlargement, and modernization of national road and rail networks with the aim of providing the market with a reliable and quality network with a view to optimizing customer service [16]. To assist in the execution of these tasks, use the Artwork Management System (SGOA). This system features several interacting modules based on the inventory that was carried out under the PRBROA, PROA I and PAP programs. This support tool for the management of works of art comprises four fundamental activities for its operation [17] as follows:

- Inventory: This is the first phase required to build the system database. It systematizes the information gathered that allows the characteristics of the artworks and the changes they have undergone to be easily accessible. The inventory is divided into three types of data: administrative (location of the work), technical (structural solution of the work) and constitution (discretization of the work in the various components).
- Inspection and diagnosis: it can be further subdivided into periodic and special inspections. The former comprise routine inspections and main inspections and it is with these that the state of the inventoried components is evaluated. In certain situations of extreme events occurring or for further investigation of any anomaly recorded in the main inspection, special inspections may be requested. This non-periodic inspection action is based on the elaboration of structural technical assessments, non-current specialized tests, dynamic tests or load tests, or analysis of periodic structural monitoring.
- Studies and projects: when there is a need for intervention in the structure, a set of tests, monitoring and evaluations is required to deepen the diagnosis and support the design of the necessary intervention on the site.
- Maintenance, repair, reinforcement and replacement: due to the anomalies found in routine inspections, there is a need to perform work to remedy the detected anomalies. Repair, reinforcement or replacement needs may also be met following major inspections. The work plan will be based on the severity of the damage translated by the state of conservation.

5. Intervention Techniques

Damage that reduces the capacity or durability of the structure has to be assessed to determine its importance in order to prioritize the interventions needed and decide what actions to take in response. This assessment also helps to establish future maintenance or replacement strategies. In the event of damage, the actions to be taken may be preventive (maintenance) or reactive (repair, reinforcement or replacement). Reactive actions are only performed when the structure or members of the structure do not meet the safety or service requirements [14]. In the scope of this investigation only the aspects related to the repair and restoration of the normal and correct functioning of the structure are considered, and this approach is not directed to the increase of the load capacity (structural reinforcement). Some of these intervention actions in the structure are:

- Repair or replacement of structural elements: the existence of elements with severe and extensive section loss in critical areas can lead to reduced load capacity, compromising the safety of the structure. In these cases, the solution may include replacing or repairing the damaged structural elements. This intervention typology can be used in case of fatigue, lack of connections and geometrical defects with and without impact signals [17].
- Structural rehabilitation: these interventions aim to increase the durability of the structure and improve its fatigue behavior. One of the techniques that can be performed is to apply high strength fiber reinforcements (FRP) to deal with damage caused by physical and/or chemical deterioration [18]. A new method of reinforcing metal structures is introduced by Weiwei Lin in [19]. This technique allows reinforcement of the superstructure and substructure of metal bridges that have fatigue problems and becomes competitive due to the fact that the intervention is fast and mitigates the impacts on the traffic during the same. It consists of changing the metal section to the composite section by integrating new structural materials that increase stiffness and load capacity.
- Repair and replacement of connections and connectors: there are several repair techniques for welded joints, as they may have cracks or high residual tensile stresses, compromising the joint and its resistance to fatigue. According to [18] the following four techniques can be used: grinding, hammering, TIG reflow and stop hole. For riveted and bolted joints, the intervention may involve replacing similar elements or replacing bolted joints with bolts, as old iron structures generally have poor weldability.
- Repair and replacement of bearings: bearings represent a fundamental element for the proper functioning and support of the structure, since the transfer of loads from the superstructure to the substructure is made through these elements. However, wear and tear, poor detailing and inadequate selection of the support typology may contribute to the degradation of the bearing. The most common anomalies in the bearings and its connecting elements are corrosion, delamination, paint or galvanization

degradation, excessive displacement, teflon and neoprene detachment, among others. Whenever there is a need for replacement of support devices or removal of the rollers for cleaning and lubrication, a tray fixing and lifting system is required.

- Repair of corrosion protection and surface coating system: steel is a material that needs corrosion protection system which can cause the structure to lose stability. These protection systems can have various defects such as cracking, blistering, dustiness, peeling and corrosion [18]. The results of the protection system condition analysis are important in deciding whether to completely replace the coating system or to partially renew the existing paint scheme. The existence of significant corrosion, with loss of metal section equal to or greater than 20%, necessitates the replacement or reinforcement of deteriorated elements [17]. Surface preparation can be carried out with water, solvents and chemicals; mechanical cleaning; or cleaning using the flame [18]. After proper surface cleaning, the protective coating is applied. Surface protection coatings can be organic, metallic or duplex systems. Organic coatings, commonly referred to as paints, are used against corrosion of metal structures and are easy to apply, unlimited size of the structures to be protected and decorative finish. Ink is sometimes confused with ink coatings, but they are distinct materials. Ink is the liquid material comprised of binder, pigments and solvents, while ink coating is the protective film that forms after drying and evaporation of the solvent and converting the binder into a solid ink film [18]. These types of coatings are applied according to a paint scheme consisting of three distinct layers: the primer, the intermediate layer and the finishing layer. They may be reversible if solid film can be dissolved using the original solvent. The use of metallic coatings implies the use of non-ferrous metals, such as zinc and aluminum, which protect carbon steel from corrosion. The solution may also go through the combination of these two systems, initially applying the metallic coating and later the organic, calling this technique the duplex system. This system's life is longer than the two types of protection used individually, as the metallic coating reduces corrosion under the duplex system and the organic coating protects the metal against early corrosion that may occur due to environmental exposure [18].
- Repair of non-structural elements: there are elements of the structure that are also susceptible to degradation and their malfunction may lead to the degradation of the remaining structural elements. Two examples are the drainage system and expansion joints. In drainage systems the accumulation of water and debris in the structure accelerates its degradation. Thus, it is necessary to create strategies so that water retention does not occur at angles and corners of the structure. These strategies may involve using slanted components and avoiding obstacles in the drainage system by being careful not to create forms that allow the accumulation and retention of solid or liquid waste. Exit channels can also be created or seal water in the hollow sections. If this is not possible, a ventilated environment should be provided to decrease the moisture content of these elements [20]. Expansion joints can be damaged due to deterioration of adhesion between sealant and floor, allowing water and debris to enter the opening. In these cases, repair or replacement of the gasket is required. Should the solution be replaced, the adjacent material must be removed prior to installing the new gasket [21].

6. Case Study

In this chapter were analyzed two cases of steel bridges rehabilitation. Information on the structures and the inspection and rehabilitation process was provided by CivilSer - Engineering Design Study, LDA.

6.1. Bridge over Ribeira do Garvão

The bridge in question is a small span bridge with a metal frame solution and reinforced concrete deck that is simply supported (figure 1) [22].

Figure 1: Bridge over Ribeira do Garvão [23].

It has a free span of 31,0m and 6,8m of board width, and the lattice metal structure is composed of two main beams with height of 3,0m (upstream and downstream) braced crosswise by transverse girder (with constant spacing of 2,86m) made of vertical flat trusses and horizontally by two braces, one at the level of the lower flanges of the main beams and another at the level of the concrete slab. The metal structure is made up of metal bars and angles of various sizes and flanges, solidified by rivets, resulting in composite profiles (“U”, “I” and “T”) [23].

One of the works in the specifications was to characterize the materials of the structure. For this purpose, tensile, chemical composition and fatigue tests were performed. The two samples were extracted near the right support, one from the lower rope core web of the upstream main truss and the other from one of the lower bracing diagonals. Four specimens were taken from each sample, two being tested for traction, one for fatigue and the other subjected to chemical analysis. In the areas where the samples were taken, the cross sections were replaced. To the core plate were added two plates which were placed laterally to the existing core plate and connected with screws, as shown in figure 2(a). The angle of the bracing, consisting of an angle, was completely cut and the continuity of the existing element was restored by placing a bolt-on angle section, figure 2(b).

Figure 2: Places of sampling: (a) lower truss rope core plate; (b) diagonal of lower bracing [22].

From the tests performed the average yield strength obtained was 265MPa and the minimum value 237MPa, while for the breaking stress the average value was 353MPa and the minimum value 329 MPa. Based on these results, the safety structure of the bridge was considered for the strength class S235 for steel of the steel frame elements. From the two fatigue-tested specimens, it was found that both resisted until the end of the $2x10^6$ cycles application, showing no cracks or breaking. From the chemical analysis it was concluded that it must be a wrought iron. The metal has a high amount of impurities, particularly phosphorus and lead, so it is not advisable to use welded joints and riveted or bolted joints should be used. In view of the results of the tests mentioned above and, based on the analysis of the structure submitted to the defined regulatory actions, a safety check was performed using calculation programs. Safety is not verified in the compressed diagonals of the main trusses in all modules. These situations result mainly from the reduction of the resistant capacity of the profiles due to the lower inertia buckling effect. In addition to these cases, the metal structure shows signs of degradation due to the widespread corrosion of the various constituent elements. Thus, the measures taken to rehabilitate this structure included replacing the fixing screws of the supporting devices, cleaning, painting and lubricating the supporting devices, reinforcing the main trusses, replacing broken rivets with screws of equivalent diameter and painting the metal elements that constitute the structure of the bridge.

6.2. Bridge over Ribeira do Vascão

The structure shown in the figure 3 is a road bridge with a steel structure solution with reinforced concrete tray that allows the passage of EN122 over Ribeira do Vascão, whose flow in the area of the artwork has approximately the South-North direction [24].


Figure 3: Bridge over Ribeira do Vascão [24].

This bridge from an old decommissioned railway bridge has a 65m span between the extreme supports, consisting of 3 spans with 20m, 25m e 20m. The deck consists of a continuous lattice beam supporting a 23cm reinforced concrete slab. The main trusses are distributed in two planes that are about 6,4m apart and the slab rests on the upper sleepers spaced 2,5m apart. In addition to the two upper and lower ropes, each of the trusses consists of vertical mullions with a 2,5m pattern, each module having two diagonals. The trusses are linked together by horizontal locking and triangular ridges. The latter are formed by diagonal bars and exist in the plane of each of the mullions. In general, the entire metal structure is made up of composite section profiles, consisting of angle or U-shaped profiles and plates with riveted connections. Between the two trusses there is a lower walkway allowing longitudinal access along the entire length of the work [25]. The test plan consisted of tensile and fatigue tests of structural steel and chemical analysis of steel. Three steel samples were taken, one from the lower rope core web of the upstream main truss near the right abutment and two from the diagonal angles of the lower horizontal brace next to each abutment. From each sample were taken three specimens, in which one was tested for traction, one for fatigue and another subjected to chemical analysis. To the core plate were added two plates that were placed laterally to the existing core plate and connected with screws, as shown in figure 4(a). The angle of the bracing, consisting of an angle, was completely cut and the continuity of the existing element was restored by placing a bolt-on angle section, figure 4(b).

a) b)

Figure 4: Places of sampling: (a) lower truss rope core plate; (b) diagonal of lower bracing near the right abutment [25].

The average yield strength obtained was 247MPa and the minimum value 235MPa, while for the breaking stress the average value is 336MPa and the minimum value is 319MPa. Based on these results, the safety assessment of the bridge structure considered the strength class S235 with f_u of 320MPa for the steel of the steel structure elements. From the three fatigue tested specimens, it was found that the Fa1 and Fa3 specimens resisted until the end of the $4x10^6$ cycles, while the Fa2 specimen reached failure in the first cycle. Failure of test piece Fa2 resulted from the fact that in the section where the failure occurred there was corrosion of the material as shown in figure. After rupture of the sample, it was found that in the section of rupture approximately 2/3 of the section area showed corrosion. It should be noted that upon prior observation of the test specimen this behavior was not to be expected as only a small surface corrosion stain was visible with no loss of section.

Figure 5: Sampling Fa2 after the rupture [25]

The chemical analysis and the information obtained through microscopic observation concluded that it is a wrought iron, material used in the early twentieth century. Steel has a significant amount of impurities, phosphorus and lead. Wrought iron is not recommended for welding and should be bonded through rivets or screws.

Structure's anomalies consisted on the poor condition of the painting and significant corrosion of the rollers and material loss by corrosion on the vertical face of the upper plate on the movable bearing. The remaining structure also had corrosion on the metal elements and the connecting elements. Corrections were based on two board rehabilitation solutions: reinforcement of existing board elements or full board replacement. The second option has the advantage of solving the corrosion problem of existing structure elements, eliminating the uncertainties associated with steel quality and the existence of non-visible corrosion of the existing structure, ensuring significantly higher levels of reliability and durability. Associated with greater ease of replacement of the assistive devices (they are corrosive and do not guarantee safety for vertical actions). The main drawback of this solution is that traffic on the EN122 needs to be interrupted for a period of at least 90 days.

Despite this disadvantage, the option selected was full board replacement, choosing a full-beam beam solution, which is quicker to assemble and easier and more economical to maintain than the triangular beam solution.

6.3. Critical analysis

The two bridges analyzed both have similar metallic structure and are of close construction times, so, as expected, it was found that the tests performed and the damage presented by the works of art are similar.

Analyzing the requested tests globally, it was found that the realization of the three types of tests was pertinent, as it allowed to understand the properties of the material that constitutes the metal structure of the bridge in question. Sampling revealed that the materials employed had similar characteristics even though they were in different locations, which could mean that the material used would be the same.

According to the table 1 it appears that the number of samples taken in bridge over Ribeira do Garvão should have been more representative, since there is no information on the constituent materials of the structure. The chosen sampling site for both cases was the area near the supports. This area, although not the most requested, has the advantage of being very accessible which facilitates the sample cutting process and reinforcement of the intervention area. The values obtained for the tensile test the material may be wrought iron, a premise that is corroborated by the characterization tests. chemistry. Through the results of this last test, the material was classified as non-weldable, with no need for further testing. For the fatigue test, it was found that the specimens being subjected to 60% yield strength for $2x10^6$ cycles did not break, this indicates that, at least in the sampling areas, the material is not micro-cracked. leading to the collapse of the material. In the case of bridge over Ribeira do Vascão, the results obtained for the tensile test and chemical characterization were similar. However, for the fatigue test, it was found that one of the test pieces, being subjected to 60% yield strength for $4x10^6$ cycles, reached failure, this indicates that the material has micro-cracks leading to early collapse of the material. This result was important as the cracking of the steel was not visible, making the cracking state of the remaining material doubtful, supporting the integral tray replacement solution to eliminate uncertainties of non-visible corrosion.

The main inspections conducted are careful in analyzing all the places that are generally critical in this type of artwork. The most common anomalies are corrosion, damage to connections, degradation of coating systems and deterioration of expansion joints. In bridge over Ribeira do Garvão the highest incidence of corrosion occurs in the upper rope of the main beams and in the transverse girder. This phenomenon can be justified by the infiltration in the expansion joints that were repaired during the 2014 inspection. Rainfall should remain for long periods on the plates and angles, allowing their infiltration and resulting in verified interstitial corrosion. The outer face of the main beams, being more exposed to weather conditions, shows the formation of moss and lichens in the lower rope of the beams, accompanied by paint blistering and corrosion in the joints between the plates and angles. It was found that the connection between the tray and the supports was weakened due to the loss of section caused by advanced corrosion, with the risk of aggravation of the anomaly compromising the functionality and integrity of the bearing. In bridge over Ribeira do Vascão the main problems due to corrosion were detected in the upper flange of the cross members that support the reinforced concrete slab, with special focus on the alignments where there are constructive joints in the concrete slab, the alignments of the bearings and the alignments of half a span of each leg. In several areas of these plates, loss of section is visible. This corrosion has a higher incidence next to concrete and can be enhanced by the expansive phenomena of concrete, namely alkali-silica reactions and the existence of carbonation of concrete reinforcement.

In the repair of the identified anomalies, the replacement of the connecting elements and the application of the coating system should be emphasized. The first action is essential to address the loss of security in calls. Bolted connections were used, where previously there were rivets, as there were no constraints on the maintenance of the structure's historical heritage and the materials were not weldable. Regarding coating systems, the correct use of the abrasive blasting method should be emphasized. The choice of the coating system could still have been the selection of a metallic coating system or a duplex system due to the strong corrosion in the structure. This factor could be more advantageous as it allows corrosion to preferentially attack the protective layer rather than the metal structure. This method tends to develop an unpleasant appearance over time, so the solution may be to select the duplex system. In bridge over Ribeira do Vascão, due to the state of degradation of the board, the rehabilitation solution was completely replaced.

7. Final Remarks and Conclusions

The need to cope the increased regulatory requirements, increased traffic and loads, degradation of works of art and limited funds for the management of structures makes necessary to have an efficient inspection policy, evaluation and further measures to make the repair process efficient. In order to systematize and optimize the inspection, evaluation and rehabilitation processes, it was necessary to evaluate each of the different phases to be able to standardize the measures to be developed in each step as much as possible. For this, the characterization tests of the materials to be performed were defined according to the available information; the *in situ* inspection process, listing the relevant aspects to be analyzed. After this information has been collected, reports are drawn up and the information is entered into a works management system and after that the most appropriate rehabilitation techniques are defined.

Comparing the two case studies to the systematized process it can be concluded that the quantity and typology of material characterization tests identified in chapter 2 corresponds to what is actually performed, however the number of tests and samples taken requested in the specifications are the smallest possible for economic reasons.

In the case of the bridge over Ribeira do Vascão, after the rupture of the specimen subjected to the first cycle of fatigue, the analysis of the state of conservation fell on the suspicion that the entire metal structure was compromised, which led to the decision to replace the entire tray. In this case, further testing could have been carried out in other areas of the structure in order to verify whether that non-visible cracking situation was representative of the overall condition of the structure. The inspection process developed for the two structures was similar and consistent with the systematized process, however it should be emphasized that no *in situ* evaluation methods were used. Inspection actions were based essentially on the visual observation of the various components of the metal bridges, verifying that the most recurrent anomalies explained in chapter 4 are consistent with those identified in the two cases analyzed. However, the need to begin introducing the use of analytical methods complementary to observation is emphasized, as some methods are relatively simple and economical and provide more information and complement visual data on the condition of the structure. It is considered that, in actual reality, these methods are not employed due to economic constraints as, as identified in section 4, some of these NDT tests imply the purchase or rental of expensive equipment. In order to achieve a cost-effective compromise, it is suggested to use less expensive tests such as the penetrating liquids method, magnetoscopy and the use of a hammer on the rivet head to test the condition of the connections. This work has been requested, but this information should already be included in the inventory component provided by the SGOA system. In order to bridge this gap, it is suggested that material characterization tests be contracted for all missing bridges. This information is essential, as it is not only relevant for conservation and maintenance actions of the built heritage, but it is also essential to assess the carrying capacity of the structure and to verify the load that it supports in a timely manner.

References

[1] P. Diamantino, "Sustentabilidade na construção metálica," tese de mestrado, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, 2014.

[2] J. Spoerl, "A brief history of iron and steel production," 2004.

[3] C. Bandara, J. Jayasinghe, P. Karunananda e U. Dissanayake, "Metals used in old Bridges in Sri Lanka and the Effects of their Material Properties on Capacity Estimations," *ENGINEER: The Institution of Engineers, Sri Lanka,* vol. L, nº 3, pp. 9-17, 2017.

[4] H. Perneta, "Abordagem sobre a evolução na construção de pontes metálicas," LNEC, Lisboa, 2010.

[5] L. Costa, Tecnologia do metal, Plátano Editora, 1981.

[6] J. Pinto, "Comportamento à fadiga de ligações aparafusadas pré-esforçadas com injeção de resina," tese de mestrado, Faculdade de Engenharia, Universidade do Porto, Porto, 2016.

[7] B. Kuehn *et al*, "Assessment of existing steel structures: recommendations for estimation of remaining fatigue life," JRC Scientific and Technical Report, 2008.

[8] Standard, S.F.S.E.N., "EN 10002-1: Tensile testing of metallic materials. Method of test at ambient temperature," 1990.

[9] A. Cruz e J. Carreira, Ensaios Mecânicos, Instituto da Soldadura e Qualidade, 1992.

[10] H. Perneta, M. Correia, A. Baptista e M. Salta, "Reparação de estruturas metálicas," LNEC, 2010.

[11] T. Loo *et al*, Bridge Inspection And Maintenance System - Inspection Manual (version 3.1), Alberta Infrastructure and Transportation, pp. 7.1-8.18, 2008.

[12] T. Hopwood, G. Christopher, J. Fairchild e S. Palle, "Nondestructive Evaluation of Steel Bridges: Methods and Applications," Kentucky Transportation Center, Kentucky, 2016.

[13] A. Elbeheri e T. Zayed, "Non-destructive Evaluation Techniques for Steel Bridges Inspection," em *TAC 2016: Efficient Transportation-Managing the Demand*, Canadá, 2016.

[14] R. Poças, "Gestão do ciclo de vida de pontes," tese de mestrado, Escola de Engenharia, Universidade do Minho, Guimarães, 2009.

[15] P. Thompson, P. Bye, J. Western e M. Valeo, "Risk assessment for bridge management systems," em *Maintenance, Safety, Risk, Management and Life-Cycle Performance of Bridges*, Austrália, CRC Press, 2018, pp. 246-253.

[16] N. Lopes, "Inspeção e Diagnóstico de Pontes Ferroviárias. Sistemas de Gestão das Obras de Arte da IP," em *Encontro 30 anos Engenharia Civil, Tomar*, 2016.

[17] S. Pereira, "Inspeção de obras de arte metálicas e mistas - Caso de estudo: Ponte de D. Luís sobre o rio Tejo," tese de mestrado, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Lisboa, 2018.

[18] H. Perneta, "Pontes metálicas em ambiente marítimo: Metodologias de avaliação, reparação e proteção," tese de mestrado, Universidade da Madeira, Madeira, 2010.

[19] W. Lin, "Rehabilitation and Strengthening of Aged Steel Railway Bridges in Japan," *Journal of Civil and Environmental Engineering*, vol. 8(2), nº 305, 2018.

[20] J. Brito e I. Flores, "Patologia e Reabilitação de Construção em Estrutura Metálica," Instituto Superior Técnico, Lisboa, 2005.

[21] NY Transportation, "Fundamentals of bridge maintenance and inspection," Nova Iorque, 2008.

[22] CivilSer - Estudo de Projetos de Engenharia, LDA, "Projeto de execução e memória descritiva e justificativa: Ponte sobre a Ribeira de Garvão," Lisboa, 2016.

[23] R. Ferreira e J. Brito, "Ensaios de caraterização do betão e do aço da obra de arte na ER389 km 32+700 – Concurso do EP nº EP/0055/2015," Instituto de Soldadura e Qualidade, Lisboa, 2015.

[24] CivilSer - Estudo de Projetos de Engenharia, LDA, "Projeto de execução e memória descritiva e justificativa: Ponte sobre a Ribeira do Vascão," Lisboa, 2019.

[25] CivilSer - Estudo de Projetos de Engenharia, LDA, "Relatório de ensaio de materiais: Ponte sobre a Ribeira do Vascão," Lisboa, 2018