JCSE The Journal of Corrosion Science and Engineering
ISSN 1466-8858 Volume 20, Paper 90 first submitted 8 October 2017
published 31 August 2018

The Impact of Design on Material Corrosion: An Illustrative Example

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Abstract

Corrosion and design make an important synergy that is often overlooked by structure designers. This causes serious complications throughout the life cycle of the project, as, with the corrosion appearance, problems such as large costs and security hazards come along. In this paper, an illustrative example of the structure of a footbridge that presents important corrosion degradation is studied. Moreover, this article shows that the design modifications that need to be implemented to prevent corrosion do not need to be grandiloquent nor make significant modifications in the conceived design. Furthermore, inspection and maintenance plans for the footbridge are presented, trying to set an example of how to design these plans effectively and to a step further than the actual approach.

Keywords: design, corrosion, synergy, footbridge, maintenance

During the design stage of a project, the engineer must take several factors into account, such as: cost, aesthetics, material mechanical properties, material availability, environmental concerns, etc. However, there is a pivotal factor that designers often overlook: material corrosion susceptibility.

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Corrosion is a process that generates huge economic losses including catastrophic failures with important environmental and social impact. The actual tendency towards corrosion management tends to be a reactive approach, in which actuations are not made until the deterioration process is notorious. This needs to be reverted, substituting the reactive approach for a proactive attitude, wherein the focus must be put on preventing the appearance of the corrosion.

The most effective way to achieve this goal is to act from the design stage, a phase of the project that is directly linked with material corrosion and the moment in which the engineer has the biggest impact in the outcome of a project.

In this paper, the synergy between corrosion and design is studied via an illustrative example: a relatively new, large footbridge, located in the north of Spain, which shows evident signs of corrosion.

1. Background

The synergy between design and corrosion has been a matter of study, since, at least, 40 years ago. Pludek (1977) made an exhaustive description of a vast number of design mistakes in which the designer may incur, describing its consequences and providing solutions. He also states that a preventive approach is the best response against corrosion problems, and that a large percentage of corrosion provoked failures could have been avoided if the design-corrosion synergy would have been considered.

Landrum (1992) also studied the aforementioned synergy, presenting design solutions considering the corrosion attack morphology and analysing the complications introduced during manufacturing processes, fundamentally in those caused by welding.

Furthermore, international normative, such as UNE-EN ISO 12944-3, provides a large amount design good practices that can be of use by the designers to conceive corrosion resistant structures. The previously mentioned norm, specifically says: "It is strongly recommended that the designer consults a corrosion protection expert at a very early stage in the design process".

Simancas & Morcillo (1998) carried out a long-term study (8 years) about the behaviour of several protective paint systems, with different coating thicknesses and metallic surface states (grinding, roughness level, etc.). They observed that alkyd and oil-based paints offer a lesser protection than epoxy and polyurethane, and that sandblasting generated much better results than manual mechanical preparation.

Goto & Kawanishi (2004) comparatively evaluated the impact of various reparation methods in steel structures with corrosion-caused section loss. They considered the deformation caused by the fact that, due to the loss of section, the structure is faced with stresses not contemplated during the design stages, causing higher displacements than those calculated in design. They concluded that direct reparation without restoring the initial position by jacking is the best option both mechanically and economically.

Shifler (2005) claims that the process of design must consist in the combination of a proper material selection, adequate geometries and joining methods and the choice of an appropriate corrosion control method. He also states that with the application of these practices it is possible to prevent or slow the corrosion process and minimize its impacts when it occurs.

Nicolai et al. (2009) tried to determine the optimal maintenance plan for a paint-protected steel structure, considering three maintenance scenarios: partial repaint, total painting over the corrosion products or total painting removing the corrosion products. They reached the conclusion that the optimal maintenance plan does not exist, as the multitude of factors impacting the corrosive process impede the existence of an optimal sequence of maintenance actions.

Emami & Toubia (2016) compared the anticorrosive behaviour of a traditional 3-layer coating system (Zn primer, epoxy intermediate coat and urethane finish) with a modern 2-layer one (Zn primer and polyxiloxane finish). The results shown that the modern 2-layer coating system provides better anticorrosive properties than the traditional one.

Garbatov et al. (2016) studied the effect that three different maintenance actions have on the mechanical properties of a corroded element: sandblasting, sanding and no maintenance. The experimental results shown that the sandblasted specimens offered the best mechanical properties, followed by the not maintained and finally, the sanded ones.

Momber (2016), with an extensive research of 750 samples into the protective coating of offshore wind generators, concluded that the majority of the coating damages were caused by design mistakes and afterwards exacerbated by mechanical stresses.

Odrobiňák & Hlinka (2016) evaluated the deterioration of 7 footbridges with neglected inspection and maintenance plans. They affirm that it is always cheaper to implement inspection and maintenance plans than disregarding the structure until a major restoration is needed.

Not a single paper examining the synergy between the designed geometry and the anticorrosive properties of neither a structure nor a product was found during this investigation, which pinpoints the lack of practical application in this area and the innovativeness of this research.

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2. The footbridge

With the purpose of illustrating the impact of design on material corrosion, a footbridge located in Santander, in the north of Spain, is studied. Figure 1a shows an exterior view of the footbridge and Figure 1b details its dimensions in meters.

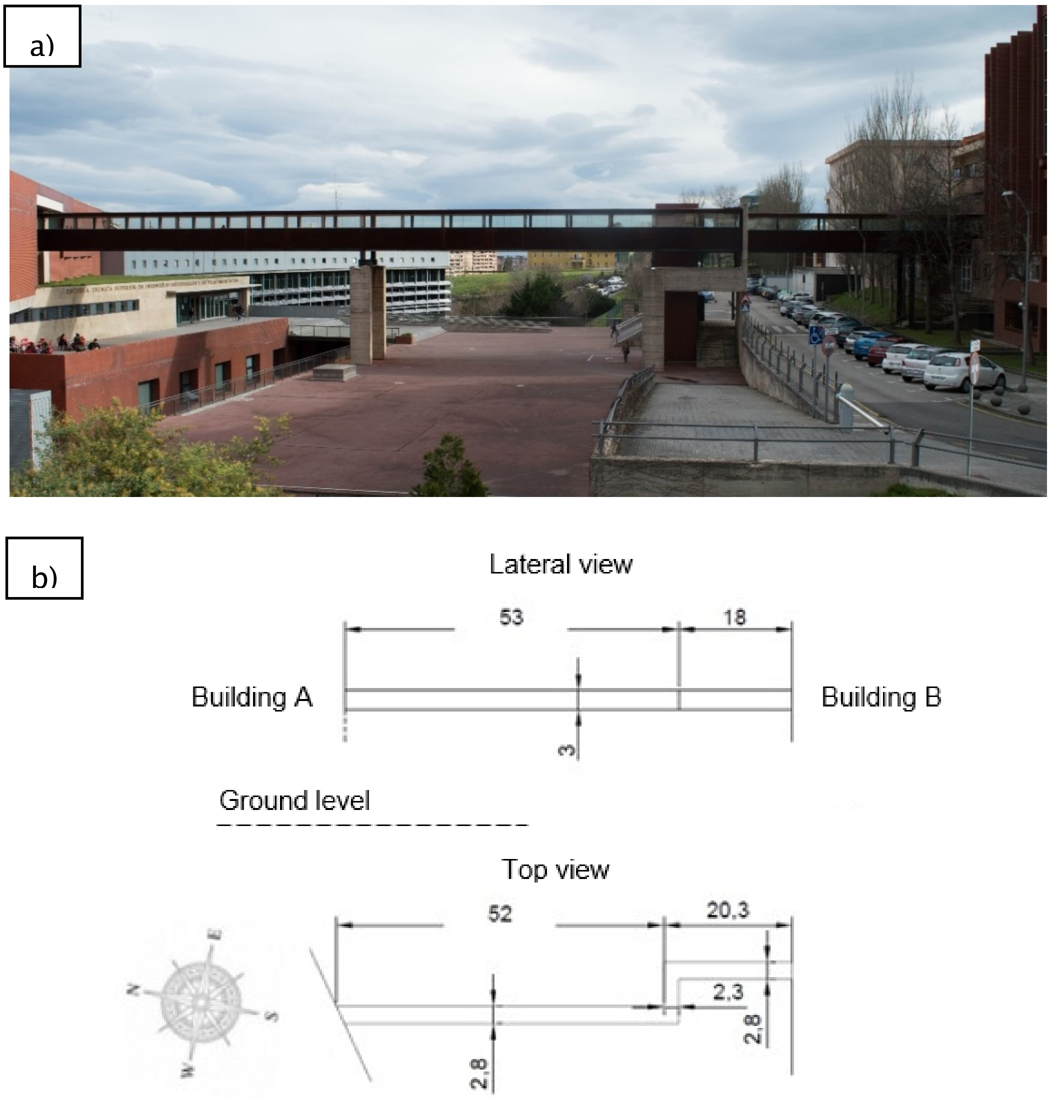

Figure 1 (a, b). Studied footbridge exterior view and dimensions

In this paper, only the interior part of the footbridge is studied, since the exterior is not possible to evaluate appropriately without the use of cranes or other elevation methods, which are not available to the authors at the moment of the study.

However, as can be seen throughout this research, the corrosion in the interior of the structure shows more than enough evidence of non-optimal design and constitutes a great base to investigate about the tremendous impacts of corrosion.

The interior of this footbridge shows enormous corrosion damage caused mainly by the combination of two factors:

a) Its proximity to the sea, since it is located less than 1km apart from the shoreline, and for this reason, exposed to a very harsh environment.
b) The structure is not waterproof, since the roof and window sealing are not effective due to the combination of lack of maintenance and improper material selection nor sufficiently protected from the aggressive environment where it is located (the floor has 5cm wide gaps in its laterals for ventilation).

The footbridge has been in service for less than 25 years, yet it shows important signs of corrosion in its steel frame structure (Figures 2 and 3), as this phenomenon has not been appropriately considered during the design stage of the project. In addition to this, maintenance has not been carried out, aggravating the corrosion problems.

These corrosion problems are of high relevance, as they provoke that the structural capabilities of the steel frame are undermined, which can potentially cause the failure of the footbridge. The structural weakening is produced because, during the corrosion process, a part of the steel transforms into corrosion products and therefore reduces the effective section of the beam and, consequently, its mechanical properties.

Figure 2. Steel frame structure of the footbridge (outlined in red)

Figure 3. Corrosion damage in the footbridge structure

Not only does corrosion entail a mechanical property loss and cause a negative aesthetical impact but also implicates high direct costs in repairs and indirect costs during the time that the structure has to be closed to the public during the restoration process (Biezma & San Cristóbal, 2005; Biezma & San Cristóbal, 2006).

3. Original design

3.1 Coating protocol

The original paint protective coating protocol consists, as described on the specification, on a mechanical preparation by brushing, followed by a brush application of two coats of not determined composition nor thickness of red-lead primer and finish standard paint respectively.

These indeterminacies in the coating protocol, combined with the lack of a maintenance program, have contributed for the quick appearance of the corrosion, and can be determined to be the root cause of the corrosion problems of the footbridge. However, the design mistakes that are addressed in the following subsections, have exacerbated the severity of the attack.

3.2 Horizontal surfaces

The structure presents a significant amount of horizontal surfaces, which difficult the drainage of the condensation liquid that drips from the windows. In Figure 4a, a schematic drawing of this problem is shown.

The retained liquid acts as the electrolyte for the corrosion reaction, which combined with the low quality of the protective coating, causes deterioration in the horizontal surfaces.

The corrosion damage caused by this phenomenon can be observed in the majority of the structure (Figure 4b).

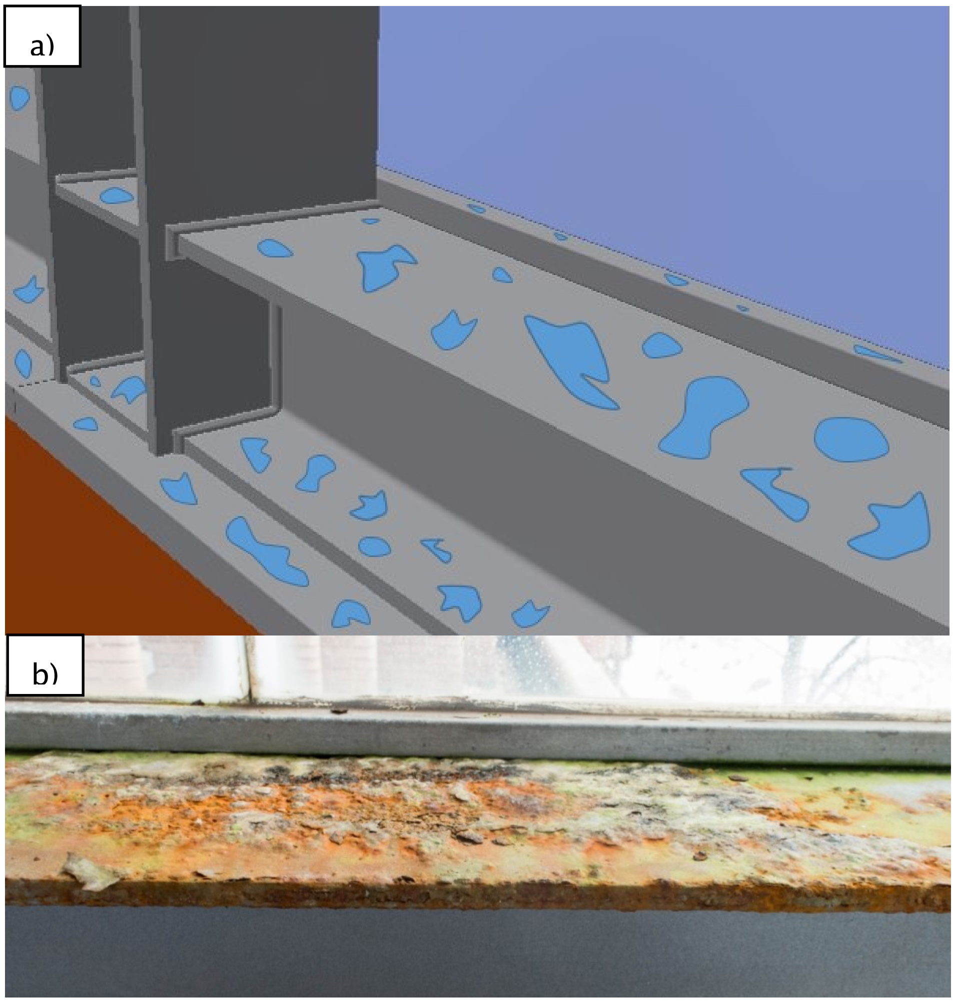

Figure 4 (a, b). Corrosion issues in the horizontal surfaces

3.3 Beam 90° edges

The geometry of the HEB structural steel beams presents 90° edges that provoke discontinuities of the coating thickness as shown in Figure 5a because, during application, the liquefied paint tends to flow away from the acute angles due to surface tension, causing a thinning on the coating. This design mistake affects both horizontal and vertical beam elements.

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As a result of this, the 90º edges of the beam act as a weak spot in which the corrosion process tends to start. Figure 5b illustrates the severe damage caused in one of the vertical beam edges of the structure.

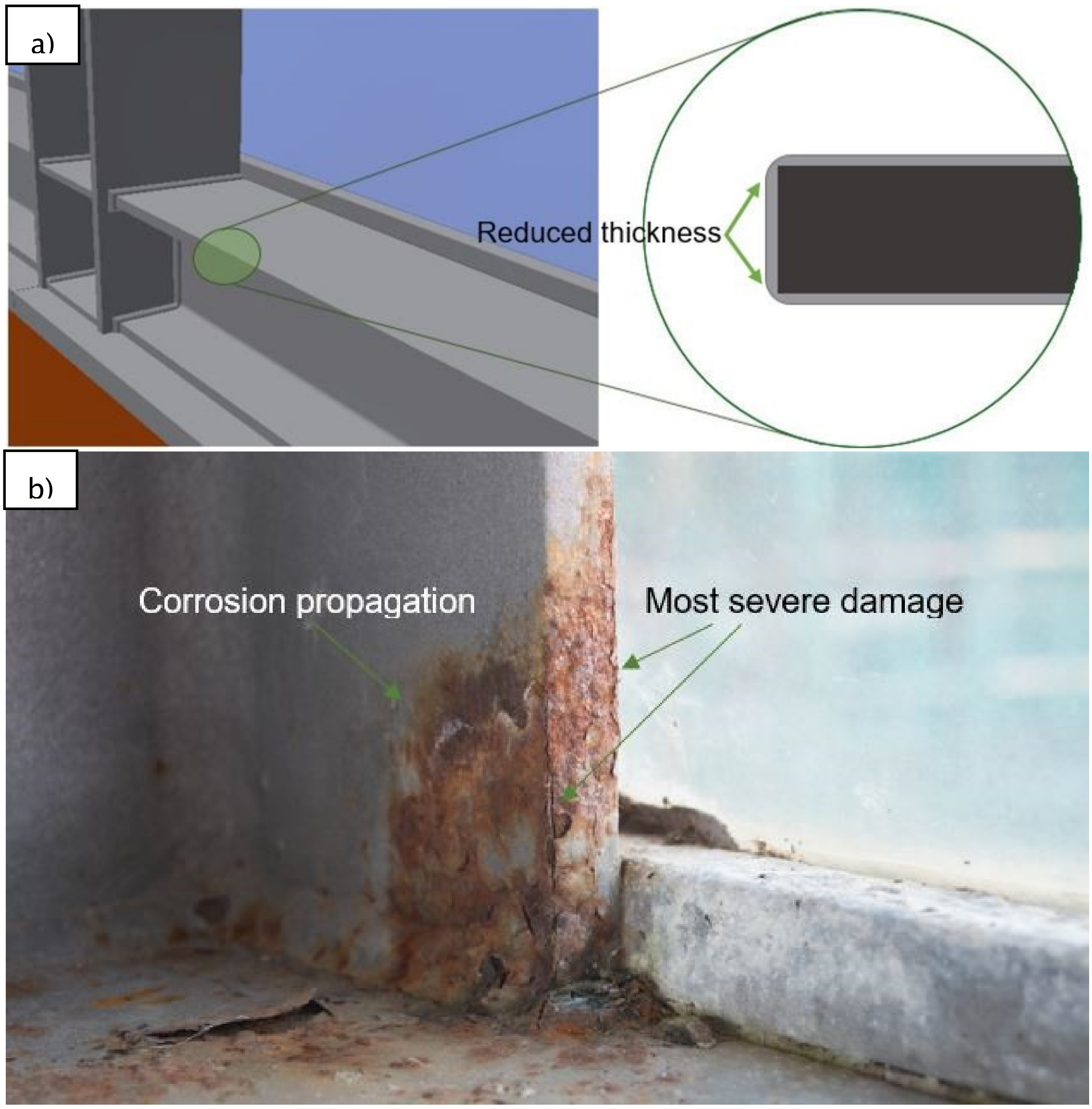

Figure 5 (a, b). Corrosion issues in the beam 90º edges

In Figure 5b, it can be appreciated that the most severe damage is localized in the 90º edge of the beam. Moreover, a propagation pattern can be observed, which means that the corrosion process began at the 90° edge and then proceeded to affect the plain surface of the beam.

3.4 Lack of access

The part of the vertical beams that faces the windows is not accessible for inspection nor maintenance, as the space between the beams and the windows is smaller than 3 centimetres (Figure 6a).

The main problem of this design mistake is that it causes the illusion that the vertical beams of the structure are not affected by corrosion, as the visible part from inside the footbridge appears to be in good condition. Figure 6b shows the posterior part of one of the vertical beams, taken by introducing a camera in the reduced space between the beam and the window, where an advanced state of corrosion can be observed.

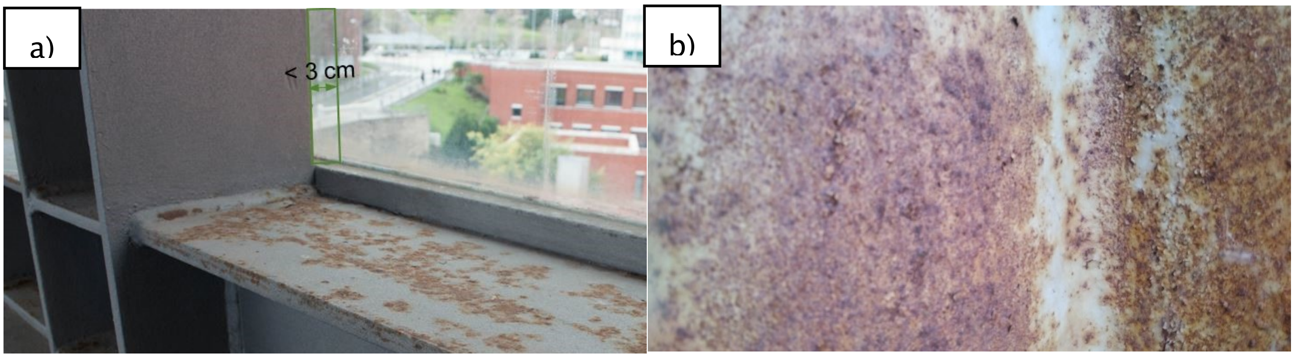

Figure 6 (a, b). Corrosion issues in the posterior part of the vertical beams

3.5 Crevices

The structure presents crevices, especially in the junction between the beams and the windows steel frames. These crevices provoke retentions of water and moisture (Figure 7a), as they allow liquid penetration and difficult drainage due to the fact that the natural airflow is reduced inside the crevice. Moreover, as the protective paint coating was applied

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after assembly, the protective layer is not uniform inside the crevice, as the paint cannot penetrate evenly.

The water retained inside of the crevice acts as the electrolyte for the corrosion reactions, causing deterioration in these areas. In this particular case, the attack in the occluded region is not caused by depassivation and coupling with an external cathode, but merely by water retention. In addition to this, the presence of chloride anions in the occluded regions causes an acceleration of the corrosion processes. Furthermore, when the corrosion process starts inside the crevice, it tends to propagate towards the rest of the beam. This phenomenon has created important damage, as shown in Figure 7b.

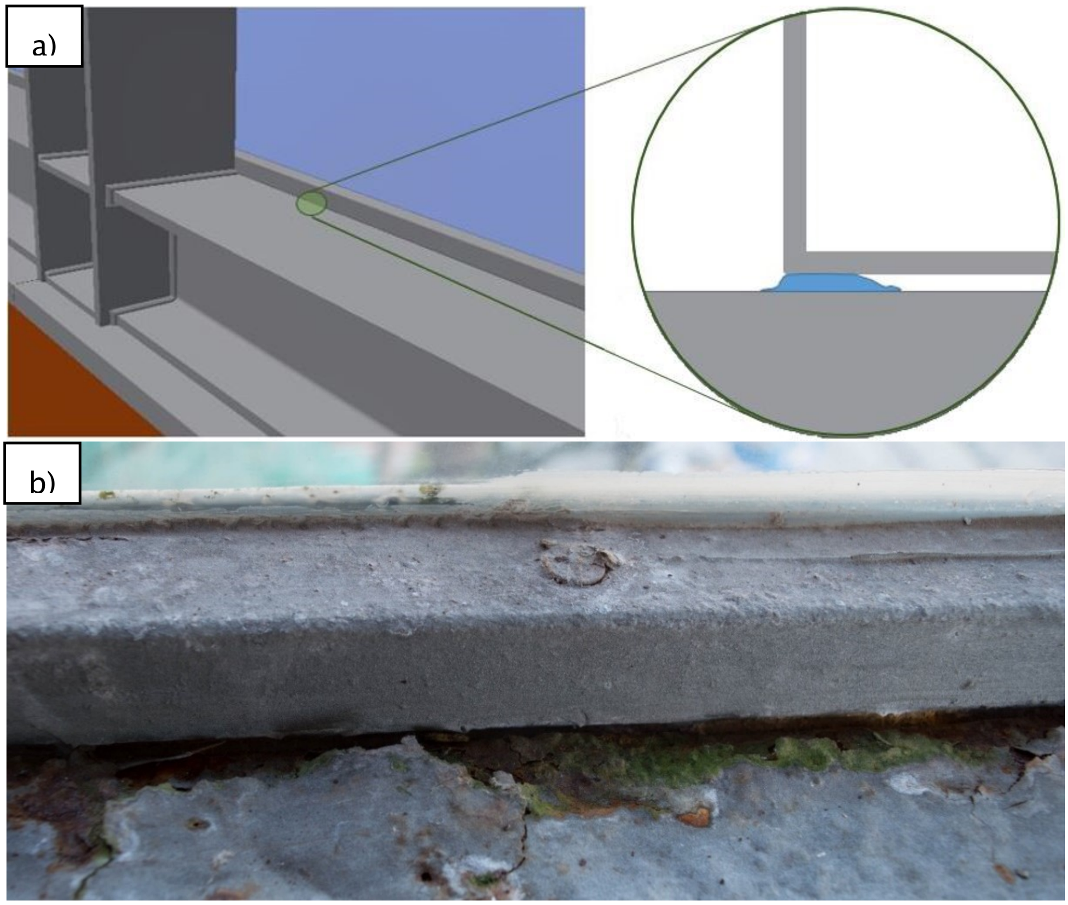

Figure 7 (a, b). Corrosion issues in the crevices

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3.6 Welding

The structural metal beams are assembled via continuous welding. Welding processes always imply the creation of weak spots in the anticorrosive protection of a structure by means the following processes:

- Firstly, the weld beads introduce geometrical discontinuity on the surface, as they add additional material. Moreover, weld beads often have porous zones (Figure 8a) that allow for liquid retention and favour the formation of not uniform coating layers.
- On the other hand, welding processes signify that the material suffers high thermal stress and, if the cooling process is not controlled, the internal structure of the welded metal is distorted, facilitating the corrosion initiation and propagation.
- Finally, if the weld is not properly cleaned, corrosion might also initiate due to flux or oxide residues.

The effect of the combination of the aforementioned processes can be observed in the footbridge structure, where the weld beads show evident signs of corrosion, as can be observed in Figure 8b.

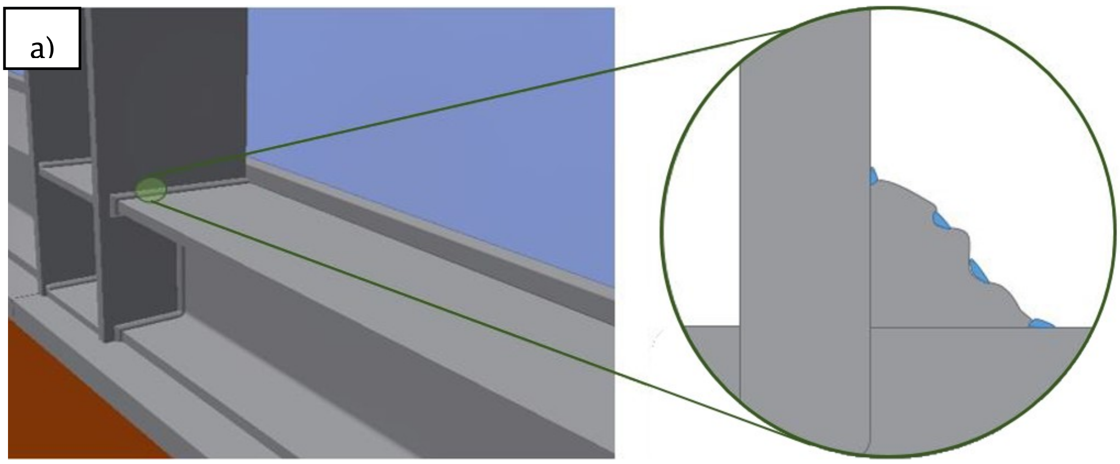

Figure 8a. Corrosion issues in the weld beads

Figure 8b. Corrosion issues in the weld beads

3.7 Bolted joints

To realize the junction between the structural beams and the window frames, a joining method via bolts was selected. Bolt heads create a geometrical discontinuity in the structure while favouring galvanic corrosion if the material of the joined metals and the bolt is not exactly the same composition wise.

The geometrical discontinuities generate water and dirt retentions (Figure 9a), while hindering the formation of a uniform protective layer. Figure 9b illustrates the discontinuities previously mentioned. Notwithstanding, this design mistake has not shown yet obvious signs of corrosion. Most likely, the root cause for the lack of corrosion products in these points, is that the bolt geometry and material had been properly selected, creating a tight seal and impeding galvanic corrosion.

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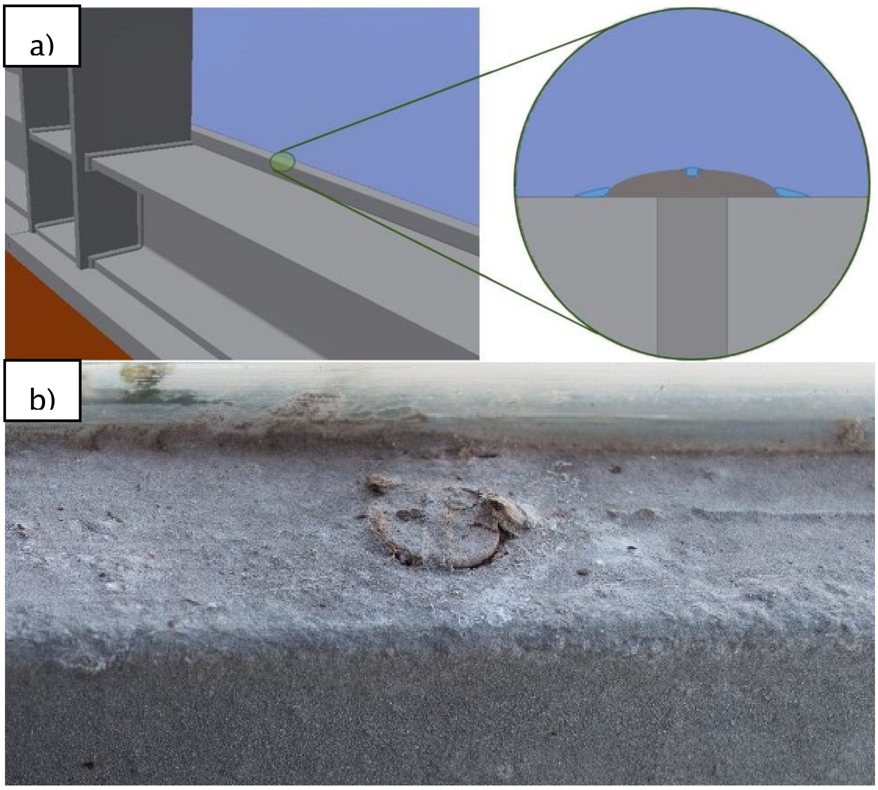

Figure 9 (a, b). Corrosion issues around the bolts

4. Proposed design

A more corrosion resistant design of the footbridge structure is proposed according to the state of the art, solving the design mistakes. Not only does this proposed design show that there is no need for pompous measures to be taken in order to increment the service life of the structure, but also that the necessary measures are totally compatible with the conceived design, not modifying the designer initial approach.

Figure 10 illustrates the proposed design. The modifications in respect with the actual design are addressed in the following subsections.

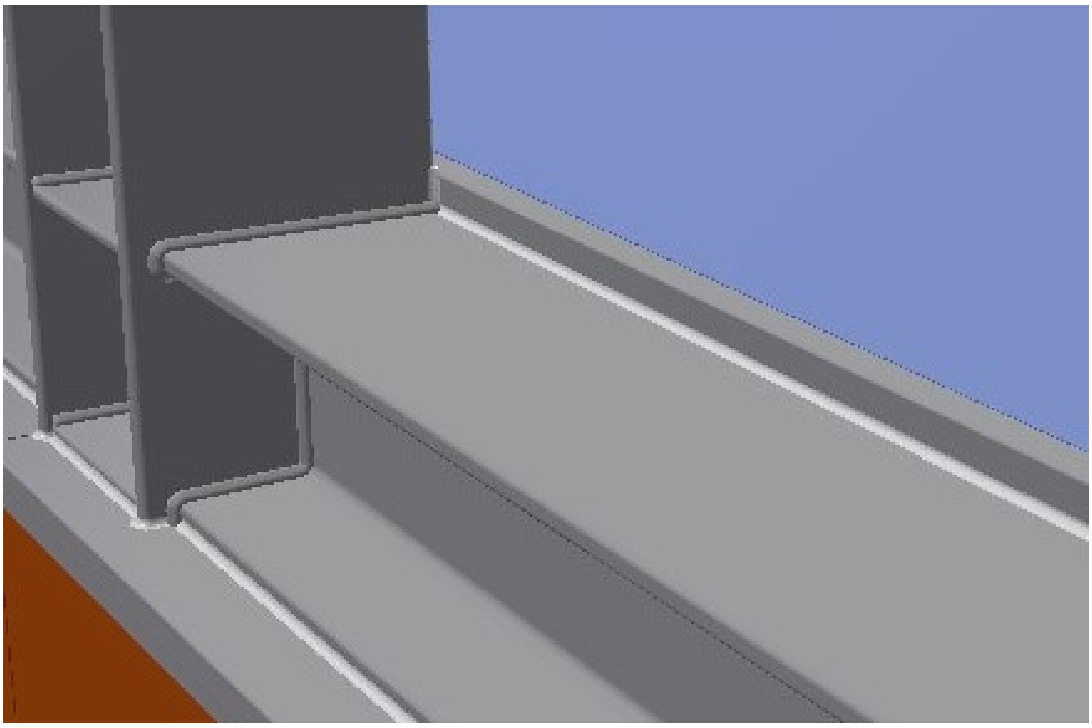

Figure 10. Overview of the proposed design

4.1 Coating protocol

The proposed coating protocol, designed with the help of the recommendations of one of the most respected coating manufacturers, is depicted in Figure 11.

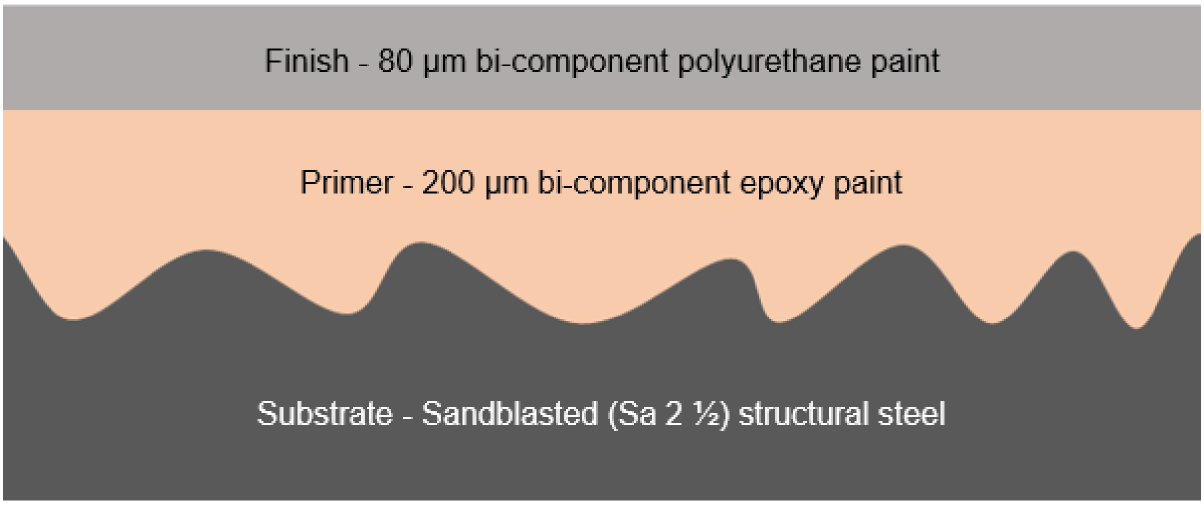

Figure 11. Scheme of the proposed protective paint system

This high quality coating protocol ensures, according to the manufacturer, at least 15 years before the first maintenance in a heavy-duty atmosphere. A long lasting coating protocol has been selected taking into consideration the actual state of lack of maintenance and the fact that some of the design mistakes cannot be solved modifying the geometry of the structure.

4.2 Horizontal surfaces

This design mistake cannot be solved geometrically without creating a great alteration in the initial design. For this reason, this complication will be addressed only with the previously mentioned long-lasting, high-quality, coating protocol.

4.3 Beam 90º edges

All of the exposed 90º edges of the beams should be machined with a 2 mm radius. This action guarantees that a uniform coating layer can be formed during the application and drying processes, as can be seen in Figure 12, thus providing the best possible anticorrosive protection.

4.4 Lack of access

As with the horizontal surfaces, this problem is not solved by modifying the geometry. The corrosion protection of the areas with lack of access also relies on the proposed coating protocol.

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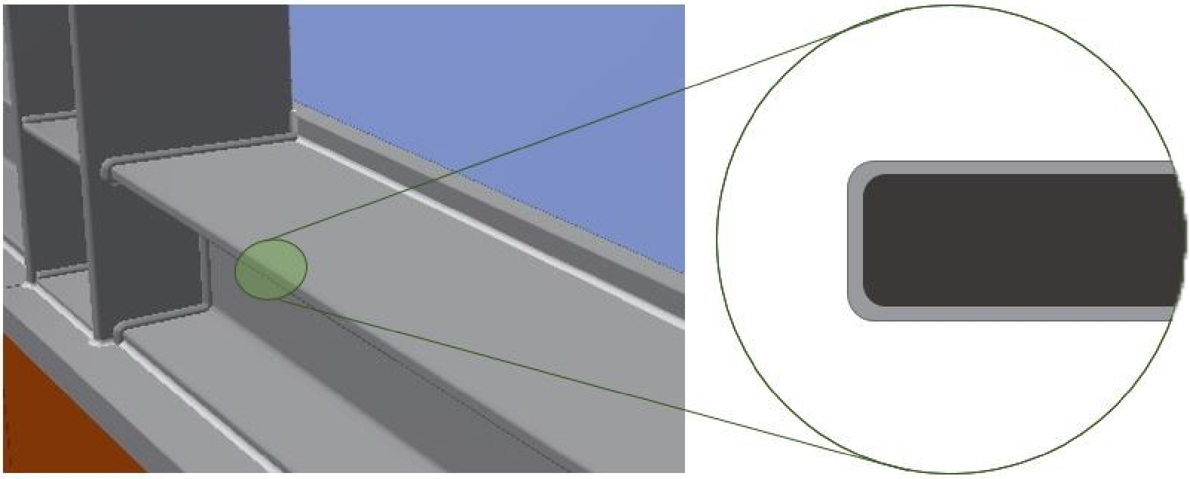

Figure 12. Proposed rounded angle design of the beam edges

4.5 Crevices

All the crevices of the structure should be sealed with a flexible rubber sealant, such as silicone rubber (Figure 13). The exterior part of the profiles (not shown in Figure 13) should also be insulated, creating an impervious chamber below the profile where water, dust, etc. are not able to introduce. This option has been chosen over continuous welding due to the fact that the window frame perimeter cannot be welded as it needs to have a certain movement freedom in order to absorb the thermal expansions.

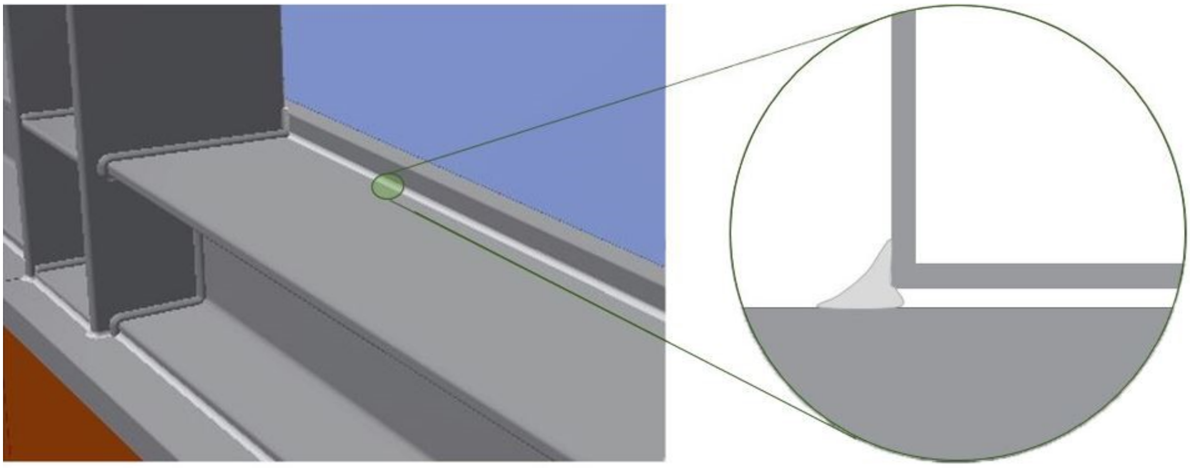

Figure 13. Proposed crevice sealing method

4.6 Welding

All of the welds of the structure should be continuous and, if needed, properly machined after application to provide a homogeneous surface (Figure 14) without any significant pores, addition material accumulations nor weld projections, so that a continuous protective coating film can be formed and dirt and water retentions are less likely to occur.

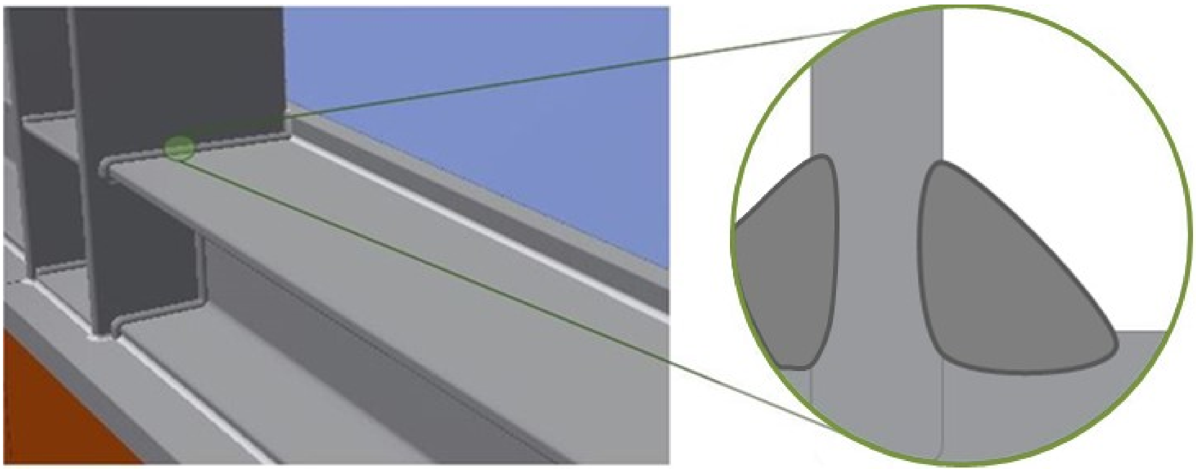

Figure 14. Proposed weld bead design

4.7 Bolted joints

The bolted joint method is maintained, because even with the actual advanced state of corrosion of the structure, the periphery of the bolts does not show corrosion signs. However, certain points need to be considered:

- The bolt size needs to be selected accordingly to provide a tight seal without protruding over the jointed parts
- The bolt material composition needs to be the same as the one of the joined metals
- The correct installation of the bolts has to be visually verified before the beginning of the coating protocol

5. Proposed inspection and maintenance plans

In order to ensure that the structure preserves its mechanical properties overtime and the damage due to corrosion is eliminated or, at least, reduced to a minimum, it is mandatory to elaborate an inspection and maintenance plan. These kinds of plans are often overlooked during the design process, which is a huge mistake.

Furthermore, it is of high importance to precisely determine the frequency, the person responsible and describe each actuation. In the following subsections, the proposed inspection and maintenance plans are presented.

5.1 Inspection plan

In Table 1, the inspection plan is summarized. In order to properly inspect the footbridge, the inspector will use the help of a small mirror to evaluate the status of the least accessible areas (see section 3.4)

Table 1. Proposed inspection plan

Description	Responsible	Frequency
Visual inspection of the protective coating, verifying the total absence of problems such as: blistering, rusting, peeling, mechanical damage	Corrosion specialist	Each 6 months
Visual inspection of the crevice sealant, verifying the total absence of problems such as: detachment, lack of adherence, seal failure, traces of crevice corrosion	Corrosion specialist	Each 6 months
Visual inspection of the window silicone seals, verifying the total absence of problems such as: detachment, lack of adherence, seal failure	Corrosion specialist	Each 6 months
Visual inspection of the windows, verifying the total absence of problems such as: cracks, breakages	Users	Continuous

5.2 Maintenance plan

In the case that, during any of the inspections, a defect is detected, the corrective actions shown in Table 2 provide solutions for all of the failure possibilities. In addition to these corrective actions, the maintenance plan is completed with several planned actions that must be carried out periodically, according to Table 3.

Table 2. Proposed corrective maintenance actions

Description of the problem	Corrective action
Presence of problems on the protective coating, such as: blistering, rusting, peeling, mechanical damage	Identification and solution of the failure root cause. Partial repaint of the affected area, which will be prepared by solvent application before applying the two coats of primer and finish specified in the coating protocol
Presence of problems on the crevice sealant, such as: detachment, lack of adherence, seal failure, traces of crevice corrosion	Identification and solution of the failure root cause. Partial elimination of the sealant on the affected zone, which will be replaced with new sealant with the original characteristics
Presence of problems on the window silicone seals, such as: detachment, lack of adherence, seal failure	Identification and solution of the failure root cause. Partial elimination of the silicone on the affected zone, which will be replaced with new silicone with the original characteristics
Presence of problems on the windows, such as: cracks, breakages	Identification and solution of the failure root cause. Replacement of the broken or cracked window, which will be installed according to the original characteristics and materials

Table 3. Proposed preventive maintenance actions

Description	Frequency
Complete cleaning of the footbridge interior, including the metal structure, which will be carefully cleaned with a damp cloth and immediately dried with a dry cloth	Each month
Complete substitution of the crevice sealant	Each 10 years
Complete substitution of the window silicone seals	Each 10 years
Complete repaint of the metal structure, with surface preparation	Each 30 years

When maintenance must be done in the least accessible areas, the only feasible option will be to remove the glass panels in the affected area and effectuate the corrective actions proposed in our plan from the outside of the footbridge, with the help of elevating machines, such as scissor platform lifts. The glass panel will be properly reinstalled after the maintenance works are completed.

6. Conclusions

This paper provides an in-depth examination of the synergy between design and corrosion, often overlooked by designers, showing a real, actual example of its impact.

Corrosion resistance is one of the most, if not the most, overlooked factors in the design of a structure. This paper proves that, in the presented particular case of a footbridge, like in most cases, the design considerations that need to be taken to improve the corrosion resistance of a structure do not need to be of high cost nor complication, but are just a matter of small modifications of the conceived design.

An adequate design must always be combined with inspection and maintenance plans that are precisely defined in accordance with the service characteristics of the structure. In the case that the inspection and maintenance plans are neglected, an important percentage of the inversion will be wasted, as high costs will have to be assumed in order to repair the structure deterioration, which will definitely occur.

The proposed inspection and maintenance plans are innovative, as in the majority of the actual structural projects, these actions are not contemplated to the extent and precision that possess the ones presented in this paper. These plans can be taken as a template by structure designers to lay out their own inspection and maintenance procedures according to the particular characteristics of each structure, yet it is especially designed for the maintenance of a glazed structural steel footbridge.

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