The deterioration of 100 years old coated steel bridges

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Abstract. Steel bridges have been widely built from the beginning of the XIX century. The structures were protected from the uniform atmospheric corrosion through Lead-containing coatings. These exhibited over the decades a very good resistance to degradation. Generally, a similar reduced corrosion was also observed for the rivets, which linked the structural elements. The degradation was mainly located in the regions directly exposed to rainfall or water flux. The formation of craters or exfoliation was only locally found. The enrichment of organic deposits promoted the permanence of humidity, which in turn, had an adverse effect on the steel conservation. Generally, the total coating thickness slightly decreased, and the long-therm protection was no longer attained. The content of Lead has a detrimental effect on the environment. Thus, the restoration works must consider the pollutant effect during its elimination and disposal.

1. Introduction
Corrosion is an electrochemical process that occurs between the metal surface and the environment. Water or humidity, gases such as Oxygen, acids or bases and salts, as for instance NaCl, promote the phenomena [1]. Corrosion protection coatings are developed and classified according to the environmental atmosphere corrosivity [2]. The classes are depending on the aggressivity, starting from a class C1 with a very low risk, to a conventional C3 medium urban environment, ending with a very high risk for industrial areas or coasts, as well as off-shore zones with an aggressive atmosphere. The system type and the layers are variable. The durability of the systems is influenced by the condition and support preparation, the coating system, the quality and the application condition, as well as the exposition [3]. The modern coating systems are divided in classes starting from a low durable system, that may reach 2 to 5 years, followed by a medium, with 5 to 15 years durability and high classified coatings, that may last beyond 15 years. Nonetheless, the durability appears to be indicative. In the past, an anti-rust orange base layer followed by an upper grey Lead-containing one were applied on steel elements. In particular, bridges and structural bars. Although in the early 1900s health hazard risk were identified, Lead was used as a paint pigment, giving a thick, resistant coatings. They do not crack during temperature variation and are resistant to wear. Furthermore, the chemical behavior also provides a good corrosion resistance [4, 5]. The goal of the present work is to characterized the main steels used and to outline the main degradation defects on old steel bridges coated with Lead-containing materials.
2. Experimental
The steel was characterized with tensile tests at room temperature [6]. The impact resistance was measured with Charpy tests [7, 8]. The specimens were oriented perpendicular to the longitudinal axes with a V notch of 45°. The tests were carried out at 20 ± 2 °C and -20 ± 2 °C with slightly reduced sections. Therefore, the measured values need to be taken as indicative. The specimens did not comply with the conventional determination of the equivalent carbon. Therefore, the weldability was alternatively tested according to a European norm [9]. The Vickers hardness across the welded profiles did not exhibit an increase in the hardness along the weldments. That means a good steel weldability. The coating thickness was measured with a magnetic induction method by using a dualscope. A very large investigation of the bridge elements was done by visual inspection. In this concern, appropriate safety concern must be taken into account (Fig. 1).

3. Results and discussion
The bridges investigated in this work were mainly built in the first years of the XIX century. The steels are usually characterized with the respect to the mechanical properties, especially by tensile tests. Although the steel type may vary depending on the structure, the mean necking limit was around 292 ± 5.4 N/mm². This is typical for a S235 steel type. The mean tensile strength was 387 ± 1.9 N/mm² and the mean strain was 37 ± 1.0 %. The impact behavior was measured by means of Charpy tests. The results exhibited a clear difference in the adsorbing energy at the different temperatures (Tab. 1).

Table 1. Charpy test results of the specimens at different temperatures.

| Denominazione campione | Temp. [°C] | Sₚ [mm²] | Energia [J] | KV [J/mm²] |
|------------------------|------------|----------|-------------|-----------|
| L1                     | 20         | 50       | 66          | 1.32      |
| L2                     | 20         | 50       | 66          | 1.32      |
| L3                     | 20         | 50       | 40          | 0.80      |
| C4                     | 20         | 50       | 45          | 0.90      |
| C5                     | 20         | 50       | 38          | 0.76      |
| L6                     | -20        | 50       | 2           | 0.04      |
| C7                     | -20        | 50       | 2           | 0.04      |
| C8                     | -20        | 50       | 2           | 0.04      |
| C9                     | -20        | 50       | 2           | 0.04      |
| L10                    | -20        | 50       | 2           | 0.04      |

Figure 1. Visual inspection on a steel bridge.
The adsorbed energy varied from 38 to 66 J at 20 ± 2 °C and was stabilized at 2 J for the specimens tested at -20 ± 2 °C. The fracture mode was ductile or brittle depending on the temperature. The chemical analysis exhibited a steel with low Carbon content (0.052 %). The steel for the rivets had a higher Carbon content (0.130 %) and also the Copper (Cu 0.015 %) was high. A relatively high Sulphur content was also detected (S 0.094 %). The low Carbon content can be correlated with a good ductility. The Sulphur lowers the ductility. The Phosphorus (P 0.044 %) implements the brittleness at low temperature.

In general, the mean coating thickness of the steel elements exhibited values ranging from 213.7 +/- 49.5 μm to 99 +/- 13.2 μm in the relatively good conserved zones. The typical environment and the corrosion products analysis of acqueous solutions indicated a low chloride and sulphate concentration, thus reducing the level of contamination. The steel coatings exhibited an anti-rust layer (orange) and a superficial cover grey colored (Fig. 2). A semi-quantitative X-ray fluorescence analysis exhibited a Lead (Pb) content up to 38% by mass.

![Figure 2. Steel coating with an anti-rust (orange) and an upper layer (grey).](image)

Generally, after almost a century of atmospheric exposure, the coating exhibited a relatively good conservation state. In general, uniform corrosion is present. By mechanical removing of the corrosion layer, there is an absence of a significant degradation (Fig. 3 left). Sporadic increased degradation remains at a superficial level (Fig. 3 right binocular lenses image).

![Figure 3. Uniform corrosion of the coated steel elements.](image)
Part of the elements protected from direct exposition to atmospheric agents exhibit a decreased corrosion (Fig. 4 left). Coatings are relatively still present, in particular on the elements sheltered from rain. Metal degradation is present along water pathways as well (Fig. 4 right).

Figure 4. Correlation between corrosion and direct-indirect exposition to the atmospheric agents.

The rivet heads generally exhibit a slight uniform corrosion (Fig. 5 left). A similar reduced degradation is also present along the rivets, once extracted from the holes (Fig. 5 center). On the other hand, these parts of the structure can be especially critical with respect to the environmental degradation. In the bridge support regions, the corrosion may exhibit an advanced corrosion stage, with thickness loss of the metal elements, such as for instance the rivet heads (Fig. 5 right).

Figure 5. Corrosion stage of the rivets and rivet heads.

Additional critical parts to be carefully considered are the concrete embedded steel regions, which may be affected from advanced corrosion (Fig. 6 left). While in some cases the rivets comes out from the bridge elements, endangering the stability of the elements (Fig. 6 right).

Figure 6. Steel bridge support region in contact with the cementitious material (left). Rivets detachment (right).
Enriched organic and inert deposits may act as humidity catcher, thus promoting corrosion. These deposits are present at the base part of the structures, often when the steel elements are anchored to the basement (Fig. 7 left). Some elements next to each other may create empty narrow spaces, that promote enrichments of deposits (Fig. 7 right) and humidity. Therefore, it is necessary to periodically clean these zones, to avoid corrosion.

![Figure 7. Organic deposits along the steel elements.](image)

The deposit points have to be cleaned to avoid permanent presence of humidity and corrosion. In points subjected to major fatigue, the corrosion products need to be eliminated in order to investigate the presence of microcracks.

**Conclusions**

The steel bridges built over a century ago often exhibit mechanical parameters of steel type S235. The conservation state of the Lead-enriched coatings is generally good. Uniform atmospheric corrosion takes place on a superficial level. Supports may exhibit an advanced corrosion stage with the formation of craters and steel thickness reduction. Exfoliation is caused by the enrichment of organic deposits as well as the long-term permanence of humidity. The steel supports embedded in concrete might be critical with respect to corrosion. In this latter case, the deterioration must be investigated with additional techniques, such as corrosion potential, pulse measurements and radar. The Charpy tests indicated the structure to be subjected to brittle fracture at low temperature in case of impact load. Generally, the steels exhibit a low Carbon content, which correlates with a good ductility and weldability. Nonetheless, the coatings thickness is no longer sufficient to guarantee future protection. Therefore, the old coatings need to be eliminated and accurately treated, considering the Lead content and the environmental issue to be respected.

**Acknowledgements**

The authors would like to thank Peter Heimgartner from Qualitech AG for the discussions.

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